DANGEROUS GOODS PANEL (DGP)

TWENTIETH MEETING

Agenda Item 2: Development of recommendations for amendments to the Technical Instructions for the Safe Transport of Dangerous Goods by Air (Doc 9284) for incorporation in the 2007-2008 Edition

EXCEPTIONS FOR FUEL CELL CARTRIDGES AND SYSTEMS CARRIED BY PASSENGERS AND CREW

(Presented by U.S. Fuel Cell Council)

The attached documents contain background information on exceptions for fuel cell cartridges and systems carried by passengers and crew.

IEC 62282-6-1Micro Fuel Cells – Safety

Summary of the standard

Published by the International Electrotechnical Commission

IEC 62282-6-1 will be published by the International Electrotechnical Commission (IEC), the electrical counterpart of the International Standards Organization (ISO).

Covering Small Low Power Systems

This consumer safety standard covers small “MICRO” fuel cell power systems and fuel cartridges that are easily carried by hand, with outputs that do not exceed 60 Volts D.C and 240 Watts. They might be used to power laptop computers, PDAs, or entertainment devices. The cartridges covered by this standard are designed not to be refilled by the consumer.

Designed to be Safe – FMEA / Hazard Analysis Is Required

This specification establishes requirements for all fuel cell power systems, units and cartridges to ensure safety for normal use, reasonably foreseeable misuse, and consumer transportation of such items. A Failure Modes and Effects Analysis (FMEA) or equivalent reliability analysis must be conducted by the manufacturer to identify faults which can have safety related consequences and the design features that serve to mitigate those faults. The analysis will include consideration of failures that may result in leakage, and mitigation to avoid leakage. Fuels and Technologies Covered

1. Methanol that is used directly to produce electricity in the fuel cell unit – Direct Methanol Fuel Cell (DMFC)
2. Methanol, converted to Hydrogen that is immediately consumed to produce electricity – Reformed Methanol Fuel Cell (RMFC)
3. Formic Acid – Proton Exchange Membrane (PEM) Fuel Cell
4. Hydrogen Stored in Hydrogen Absorbing Metal Alloy – PEM Fuel Cell
5. Methanol Clathrate Compound – PEM Fuel Cell
6. Borohydride Compounds – Direct and Indirect, solid and liquid formulations
7. Butane – Solid Oxide Fuel Cell

Note: Fuel 1, methanol or methanol / water solution, is covered by the main body of the standard. Annexes A through F cover other fuels and technologies listed 2 through 7.

General Design Requirements Included to Avoid Risks of:

- Fire
- Explosion
- Leakage
- Harmful Emissions
- Ignition Sources
- Corrosion

Design Must Handle, Without a Leak

- Temperature Extremes (-40º C to +70º C)
- Vibration (up to 8 G acceleration)
- High Internal Pressure (95 kPa or twice the working pressure at 55°C, whichever is greater)
- Low External Pressure (95 kPa differential)

- Crushing (100 kg for cartridge)
- Dropping (1800 mm for cartridge)
- One Thousand Connections and Disconnections

Fuel Cartridge Fill Requirement

The fuel cartridge design and fuel fill amount must allow fuel expansion *without leakage* to a cartridge temperature of 70º C with either the cartridge alone or constrained by the system.

Control Systems Must Fail Safe

- During the course of normal usage, in case of controller malfunction, safety shall not be compromised, namely the fuel system shall not be heated abnormally, and fuel shall not leak.
- During the course of normal usage, safety shall not be compromised in cases where a portion of the control circuit becomes short-circuited or disconnected, namely the fuel system shall not be heated abnormally, and fuel shall not leak.
- After abnormal operation or a single fault, the equipment shall still be in full working order.

Usage Instructions Will Include:

- Safety instructions and warnings.
- Text or markings on the system indicating that the system complies with IEC 62282-6-1.
- Amount of fuel in the cartridge.
- Information that identifies the manufacturer of the unit and/or system, including company name, address, telephone number, and web site.
- All micro fuel cell power units and micro fuel cell power systems shall identify the fuel supply cartridge(s) which are acceptable for use with the units and systems.

Extensive Type Testing is Required:

Test item	Test sample
Pressure Differential Tests	Fuel cartridge & Micro FC power unit and/or power system
Vibration test	Fuel cartridge & Micro FC power unit and/or power system
Temperature Cycling Test	Fuel cartridge & Micro FC power unit and/or power system
High temp. exposure	Fuel cartridge
Drop test	Fuel cartridge & Micro FC power unit and/or power system
Compressive loading test	Fuel cartridge, Partially filled cartridge & Micro FC power unit and/or power system
External short-circuit test	Micro FC power unit or power system
Surface and exhaust gas temperature test	Micro FC power unit or power system
Long-term storage test	Fuel cartridge
High Temperature Connection Test	Fuel cartridge & micro FC power unit
Fuel cell power unit Internal pressure test	Micro FC power unit with a pressurized empty fuel cartridge
Emission test	Micro FC power unit or power system
Connection cycling test	Fuel cartridge and micro FC power unit

Micro Fuel Cell Emissions are Limited to Avoid Toxicity based upon World Health Organization and US OSHA limits

ICAO Member Briefing

Passenger and Crew Exception for Borohydride Powered Micro Fuel Cells

July 28, 2005

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Introduction

This white paper provides a background briefing and risk analysis in support of the Unites States Fuel Cell Council (USFCC) proposal to ICAO asking for an exception to allow micro fuel cell power systems and cartridges on board passenger aircraft. This paper specifically addresses sodium borohydride and potassium borohydride (alternatively, "borohydrides") based micro fuel cell systems and why they can safely be allowed onboard passenger aircraft.

Background

As portable electronic devices continue to evolve, current battery technology is not keeping pace with increasing demands for power. Consumer electronics manufacturers are developing micro fuel cell technologies to power the next generation of modern devices. Micro fuel cells represent a completely new technology, relying upon fuels such as sodium borohydride and potassium borohydride to generate electrical power, rather than the alkaline, NiCd, NMH and lithium chemistry found in current primary and secondary batteries today.

Micro fuel cell developers are committed to designing and building systems that meet stringent safety standards that ensure that this technology is safe for consumers to use and transport. Technical experts from across the micro fuel cell industry have developed a comprehensive micro fuel cell safety standard (IEC-62282-6-1) that these systems, and their fuel cartridges, will be required to meet prior to use on aircraft. This standard complements existing standards and regulatory requirements for consumer electronics products which will also apply to micro fuel cell systems. In addition, for use on aircraft, fuel quantities will be limited to 200 g for solid fuel and 200 mL for liquid fuel.

Borohydride Based Fuel Cell Systems

Fuel cells work on the principle of electrochemical oxidation of a fuel to create electricity. The fuel can be hydrogen stored as a high pressure gas or absorbed in a metal hydride; fuel can be an organic fluid such as liquefied butane, methanol or formic acid; or fuel can be a salt—such as sodium or potassium borohydride--or salt solution as in the case of this document. Borohydrides have some distinct commercial and safety advantages which makes them particularly well suited for portable electronic applications.

For a viable and compelling fuel cell product, methods for providing a safe and affordable high energy density fuel are required. Micro fuel cells using borohydrides achieve this, and can generate electricity in two basic ways.

> **Direct Borohydride Fuel Cell (DBFC) System.** In this type of system a liquid (solution) formulation of borohydride is used directly as the fuel at the anode (negative terminal) of a micro fuel cell.
>
> **Indirect Borohydride Fuel Cell (IBFC) System.** In this type of system a solid or liquid (solution) formulation of borohydride is processed into hydrogen, which is then immediately used as the fuel at the anode of a micro fuel cell.

In both cases air is required at the cathode (positive terminal) of the micro fuel cell. In this process oxygen from air reacts—via the fuel cell—either with the sodium or potassium borohydride itself (DBFC systems) or with the hydrogen released by the sodium or potassium borohydride (IBFC systems). The only product emitted into the air is water vapor; the byproduct from using borohydride fuel (an alkaline borax salt) is retained within the system for subsequent disposal or recycling.

In the case of IBFC systems, hydrogen is present only as a transient material and it is not stored or transported in significant quantities. Both IBFC and DBFC systems require water, either as a separate liquid fuel component or as the solvent for liquid sodium or potassium borohydride fuel formulations; in IBFC systems it is the combination of water with the sodium or potassium borohydride that releases the hydrogen.

Direct and indirect borohydride fuel cell systems are an extremely clean source of power, without the dangerous emissions associated with a combustion process and with no risk of emission of volatile organic fuel components or byproducts. These devices present an attractive alternative to the ever-increasing volume of batteries now being brought aboard passenger aircraft.

Borohydrides as Fuel

Typically, sodium borohydride is the borohydride compound employed; potassium borohydride can also be used. The borohydride may be used as the pure dry solid or as a liquid or solid formulation including solvents, stabilizers, catalysts or other additives. The most common stabilizers used are strong bases (caustic materials) like sodium or potassium hydroxide, similar to the caustics used in several current battery technologies. The most common solvent used is water. Properly stabilized with caustic, sodium or potassium borohydride will lose less than 0.01% potency per year at typical storage conditions

Most formulations of borohydride used as fuel, in solid and liquid form, are stabilized with caustic and are class 8 packing group II materials that are currently allowed as cargo on passenger aircraft (example: UN 3320).

Pure, dry sodium or potassium borohydride can also be utilized as fuel. These are class 4.3 (dangerous when wet) packing group I materials that are currently forbidden for transport as cargo on passenger aircraft. Precedence for similar materials that are nevertheless included within devices currently allowed for in cabin use include: Lithium (UN 1415), Magnesium (UN1418), and Zinc (UN 1436) – all used within some types of batteries or related energy storage devices.

These materials all have strong industrial and transport safety records and have been transported and used in significant quantities for over 50 years.

Risk Management

This section provides an overview of the risk management strategies in place to assure safe operation of direct and indirect borohydride fuel cell systems. The appendices that follow provide additional information.

The primary risks associated with micro fuel cells using borohydrides derive from (a) the energy content of the fuel, (b) the reactive nature of the fuel (water reactive and/or corrosive) and (c) the transient presence of hydrogen (a flammable gas) in IBFC systems. Subsidiary risks include thermal hazards from any components of the system that operate above room temperature and consumption of oxygen by the fuel cell system.

These risks are all managed by the requirements of the USFCC proposal to ICAO and by the design and certification requirements that have been established.

Sodium and potassium borohydride are energy rich materials (as are components of batteries, methanol, butane, formic acid and hydrogen). Each gram of sodium borohydride can be used to produce up to 7 Watt-hours (Wh) of heat or electricity. In practice it produces both, but higher fuel efficient devices produce more electricity than heat. It is this energy richness that makes these compounds useful, and which leads to their reactivity. The proposed exception for these systems limits the amount of fuel to 200 g (solid) or 200 mL (liquid). The maximum amount of energy these amounts can contain is 1.4 kWh. Certification requirements also call for careful management of the release of this energy and are covered in Appendix A.

The most reactive form of these fuels is the pure, dry powder form of sodium or potassium borohydride which is a class 4 division 4.3 (dangerous when wet) packing group I material. This classification arises because the uncontrolled mixing of sodium or potassium borohydride with water releases hydrogen. It is, incidentally, this very feature of sodium and potassium borohydride which makes them useful in IBFC systems where hydrogen is produced for use by a proton exchange membrane (PEM) fuel cell. Because IBFC systems are designed to contain and deliberately mix materials whose combination releases a flammable gas, these systems can include materials which are normally considered incompatible. This risk is managed in two ways.

First, certification requirements for systems that contain incompatible materials call for two independent means of preventing inadvertent uncontrolled mixing of these materials during transport and storage. This is modeled upon existing oxygen generator regulations.

Second, there are IBFC systems where the borohydride is formulated so that they are no longer dangerous when wet materials. These formulations test as Class 8 (corrosive) packing group II materials and remove the hazard of water reactivity. These systems may still contain a second liquid fuel component that reacts with the sodium or potassium borohydride fuel to release hydrogen, and in this case the design constraint of two independent means of preventing inadvertent uncontrolled mixing during transport and storage remains in place.

There are also both IBFC and DBFC systems which use liquid class 8 formulations of sodium or potassium borohydride and which do not contain a second liquid fuel component that can react with the borohydride fuel to release hydrogen.

Because all forms of borohydride fuel are at least class 8 materials, they all pose hazards of corrosivity. This hazard is managed by strict certification requirements mandating that the system not leak and undergo extensive type testing for verification (Appendices A and B).

The cartridge and system fuel connectors also must be designed to only allow fuel to flow when sealed to the proper mating connector. Upon disconnection from the fuel cell power unit, the connectors shut and stop fuel flow immediately. Certification requirements include strict 'no leakage' criteria for fuel cartridges, even during repeated mating and un-mating cycles.

Sodium and potassium borohydride fuels also happen to have good warning properties. The salt solutions form a crusty white deposit similar to those that form during alkaline battery leakage. This leakage is easily seen and avoided should a leak occur, and even dilute fuels would have a terrible flavor discouraging ingestion.

Hydrogen is present in transient amounts within IBFC systems. Management of this risk is an intrinsic feature of IBFC systems: hydrogen is only produced when required for use by the fuel cell, and not inventoried or stored in significant quantities. Further management of this risk is provided by the certification requirement that any single point emission of hydrogen be below the level capable of sustaining a flame and that total emissions always remain below the level sufficient to create a flammable atmosphere under poorly ventilated conditions (1 m^3 volume, 10 air changes per hour).

Borohydride fuel cell systems are monitored by passive control mechanisms and active electronic control systems which will shut down the system—stopping any hydrogen or power production immediately—if a fault condition is detected or a leak develops. These systems are also designed to fail safely and not operate if the electronic control system is not functioning.

Hydrogen can also be generated in DBFC systems, but the generation rate is controlled chemically by the caustic stabilizer and much of the generated gas is consumed in the fuel cell. The generation rates are far below the permissible venting limits required for certification.

Additional general safety features of these systems include the aforementioned control electronics that monitor system parameters. These can trigger a system shutdown and cease the flow of fuel in the case of any critical failures, including abnormal temperatures, excessive fuel consumption, excess current draw, unrecoverable voltage drop, or similar events. Certification standards require validation of these control strategies and designs through exhaustive failure mode and effects analysis (FMEA). Through this comprehensive monitoring, the system will also detect an abnormal external condition, such as excessive load or short-circuits, and cease operation. System electronics are designed and tested to necessary levels of electromagnetic compatibility (EMC) to ensure reliable operation of the safety control systems and prevent effects on any other near-by electronic devices.

Certification requirements impose additional general safety precautions covering both normal use and reasonable abuse situations. Specific requirements include pressure differential tests (altitude simulation) specifically designed to emulate use in an aircraft, vibration tests, high temperature exposure and temperature cycling tests, drop tests, compressive loading tests, short circuit, exhaust gas temperature, cartridge connection cycling tests, water immersion and emission tests. Certification standards will be enforced by the requirement of the USFCC proposal to ICAO that only certified and marked devices be permitted onboard. The underlying safety standard (IEC-62282-6-1) is on schedule for final approval by the IEC before the end of 2006.

Appendix A: Risk Mitigation Analysis

The risk analysis of this appendix highlights the various product design controls and qualification testing activities mandated for borohydride based fuel cell systems by safety testing and certification requirements that are intended to prevent critical failures and eliminate unacceptable risks. The table below summarizes potential risks and associated mitigations that can be demonstrated through physical analysis and/or testing to assure safety throughout the life of the product.

#	Risk Description	Risk Mitigations
1	Fuel leaks or unsafe hydrogen emissions occurs during normal use as a result of changing environmental conditions: a. High temperature b. Temperature extremes & cycling. c. Altitude change d. Vibration e. Dropping f. Crushing g. Water immersion	Fuel cartridges and systems will be designed and tested to the following tests with the common requirement of **no leakage, no dangerous hydrogen emissions, fire or explosion** for all tests: (a) Fuel cartridges will be designed and tested to withstand temperatures of 70 ^{o}C for 4 hours. (b) Fuel cartridges and systems will be designed and tested to withstand temperature cycling between -40 ^{o}C and +55 ^{o}C . (c) Fuel cartridges and systems will be designed and tested to withstand exposure to a 95 kPa (negative) differential pressure. (d) Fuel cartridges and systems will be designed and tested to withstand vibration from 17 to 200 Hz at up to 8 g's. (e) Fuel cartridges will be designed and tested to withstand drops of 1.8 m onto hard surfaces.. Fuel cells systems will be designed and tested to withstand drops of 1.2 m onto hard surfaces. (f) Fuel cartridges will be designed and tested to withstand crushing by weights of 100 kg. Fuel cell systems will be designed and tested to withstand crushing by weights of 25 kg. (g) Fuel cartridges will be designed and tested to withstand immersion underwater to 1 m.

2	Fuel leaks or unsafe hydrogen emissions occur as a result material degradation.	Fuel cartridge and system components in contact with fuel and/or hydrogen will be constructed of materials resistant to deterioration over the lifespan of the device.
3	Emission of flammable gas or formation of a flammable mixture during normal use.	Fuel cartridges and systems will be designed and tested to restrict single point hydrogen emissions to levels below that required to sustain a flame and total emissions to levels below that required to form a flammable atmosphere (10 m^3 per hour ambient air flow).
4	Rupture or failure during use results in hydrogen or fuel leak	Fuel cartridges and systems will include active electronic and passive mechanical systems to detect faults such as fuel or hydrogen flow not consistent with fuel cell output and shut down the systems if this occurs.
5	Dangerous reaction from the combination of incompatible materials.	Fuel cartridges and systems will be designed with two independent means of preventing inadvertent uncontrolled mixing of incompatible materials during transport and storage.
6	Injury due to excessive temperature.	Fuel cartridges and systems will be designed and tested to limit the maximum temperatures of exposed surfaces (metal: 50 ^oC; porcelain or vitreous material: 60 ^oC; molded material, rubber or wood: 70 ^oC).
7	Injury or damage due to electrical shock.	Fuel cartridges and systems will be designed and tested to tolerate external short circuits of 0.1 ohm; Output voltages are limited to 60 V or less.
8	Depletion of atmospheric oxygen caused by operation of the fuel cell system (19.5% minimum OSHA occupational level, 18% level is considered unsafe threshold for humans).	A 25 W sodium or potassium borohydride fuel cell operated in a 1 cubic meter volume with 10 air changes per hour (representative of minimum cabin volume per passenger and minimum air change rate) would decrease air oxygen content from 20.90% to 20.80%. Certification limits operation to 240 W or less and to systems that are wearable or easily carried by hand. Power levels in practice are expected to be < 25 W
9	Consumer Misuse	Cartridges and systems will be labeled to identify potential hazards due to misuse by consumer.

- **Appendix B: IEC 62282-6-1 Test Criteria**

Following is an abridged list of tests associated with certification to the IEC-62282-6-1 Micro Fuel Cell Safety Standard.

Pressure differential tests (altitude simulation)	The greater of 95kPa or Two times the fuel vapor pressure at 55°C
Vibration tests	7 to 200 Hz for 3 hours total with accelerations up to 8 g's
High temperature exposure tests	Four hours at 70ºC
Temperature cycling tests	Two cycles of -40 ºC to 55 ºC with four hour soaks at temperatures
Drop tests	System: 1.2 m; Cartridge: 1.8 m
Compressive loading tests	System: 25 kg; Cartridge: 100 kg
Short circuit	0.1 ohms for 5 minutes
Exhaust gas temperature tests	Less than 70 ºC
Long-term storage	28 days
Cartridge connection cycling tests	System: 1000 cycles; Cartridge: 10 cycles
Hydrogen leakage test	Less than 0.0162 mg/hr (0.018% vol)
Emission tests	All emission must be below limits recommended by the WHO/ILO for occupational safety.
Water immersion test	30 minutes below one meter of water

Certification criteria include a stringent "No leakage" requirement which prohibits consumer contact with any accessible fuel from the system, and an additional "No dangerous emission of Hydrogen" requirement which is below the minimum mass loss rate capable of:

1. sustaining a flame
2. producing the Lower Flammability Limit in a 1 cubic meter volume with 10 air change per hour

ICAO Member Briefing

Passenger and Crew Exception for Fuel Cells Powered by Formic Acid

July 28, 2005

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FORMIC ACID FUEL CELL (FAFC) SYSTEMS RISK ASSESSMENT/ANALYSIS
(July 28, 2005)

SUMMARY

This submission includes additional information on formic acid fuel cell (FAFC) systems to further the understanding of the potential safety risks with FAFC systems in consumer products and the risk mitigations incorporated into this specific technology (presented as a risk assessment/analysis). These risks have been considered in establishing the safety requirements in the IEC 62282-6-1 (Micro fuel cell safety standard) for FAFC power systems, units and cartridges, to achieve a reasonable/acceptable degree of safety for normal use, reasonably foreseeable misuse, and consumer transportation of such items.

This following risk assessment/analysis done on the FAFC system (fuel cell power unit plus fuel cartridge) demonstrates that these systems can be designed, built and tested/qualified such that they will be safe for transport and use in passenger aircraft cabins.

Background information on the system is also provided to aid in the understanding of the risk assessment discussion.

BACKGROUND

SYSTEM COMPONENTS

The main components of a FAFC system are the fuel cell module, the formic acid fuel cartridge, the fuel flow pump and valves, the power management and control electronics and the by-products exhaust and containment systems.

PHYSICAL AND FUNCTIONAL DESCRIPTION

The FAFC power systems discussed in this document have the following specifications:

- Fuel cell power output: ≤ 30 watts
- Cartridge size: ≤ 200 ml of fuel
- Fuel (formic acid) concentration: < 85% wt (NOT FLAMMABLE).
- Physical size: compatible with use in handheld devices

CURRENT AIR SHIPMENT PROVISIONS FOR FAFC SYSTEMS AND CARTRIDGES

FAFC cartridges will have 200 ml or less of formic acid and can be shipped as cargo under the following conditions:

- Proper Shipping Name, UN number and Packing Group
    - ➢ Formic acid, UN1779, Packing Group II

- In Passenger Aircraft Cargo
    a. **Excepted quantity** less than or equal to 30 milliliters in the inner packages that total to 0.5 liters in the outer package.

b. **Limited quantity** limit is 0.1 liters in the inner packages that total to 0.5 liters in the outer package. The inner and outer packages specifications are in the packaging instruction Y808.
c. **Fully regulated** limit is 1 liter in the inner package that totals to 1 liter in the outer package also. The packaging instruction is 808.

- In Cargo Aircraft
  - 2.5 liter inner packages that total to 30 liters in the outer packages. The packaging instruction is 812.

The fuel cell power unit (FAFC system without the cartridge but with possible residual amounts of formic acid inside the fuel cell power unit) can be shipped under the provisions of UN3363 which covers "Dangerous Goods in Machinery".

RISK/SAFETY ANALYSIS

This risk/safety analysis performed on the FAFC system highlights various product design controls and testing/qualification (risk mitigations) activities to achieve a reasonable/acceptable degree of safety for normal use, reasonably foreseeable misuse, and consumer transportation of such items. The table below summarizes those risks and risk mitigations (the design controls and test/qualification protocols) that will be checked as part of the certification of such products against IEC 62282-6-1. In the table below, the numbers in the parenthesis in front of the items in the "Risk Mitigations" column indicates connections of that risk mitigation to the numbered risks in the "Risk Description" column.

#	Risk Description	Risk Mitigations
1	**Formic acid (FA) leaks** out of cartridge from exposure to: **1. High temperature** (70^{o}C) for 24 hours, **2. Low temperature** (-40^{o}C) for 24 hours **3. Temperature cycling** (55^{o}C for 4 hours, followed by -40^{o}C for 4 hours, repeat two times with less than 3 hours interval between temperature extremes) **4. Altitude change** in aircraft transportation (equivalent to 100 kPa for 6 hours @ 20^{o}C) **5. Vibration** (sinusoidal 7Hz - 200Hz, 1gn -8gn) **6. Dropping** (from 1.8 m height as per transportation requirements and instructions) **7. Crushing** of cartridge (100 kg mass) 8. **Cartridge components/material degradation** failure during life time of the product **leading to:** - personal injury from ingestion (toxic & corrosive), skin/tissue/eye damage from contact (corrosive & toxic) - damage to equipment or carrier (corrosive, but severity of leakage is less than **severity** of the leakage of the already acceptable fully regulated amount of 1 liter formic acid in passenger aircraft cargo because of the small amounts of formic acid in the fuel cell cartridges ≤ 200 ml) **Note:** if the qualification of the fuel (formic acid) containment system in the fuel cell cartridges is done to the same or higher stringent level as the UN packaging requirements for the fully regulated shipping amount in passenger aircraft cargo then the **risk (Severity of Failure x Probability of Failure)** of leakage is less for formic acid fuel cell cartridges than the current acceptable transportation of formic acid in passenger aircraft cargo.	• (1,4) The fuel cartridge will be designed and tested for excess over pressure withstand capability (caused by high temperatures and altitude changes in aircraft of 100kPa + vapor pressure of fuel). • (1,2,3) The fuel cartridge will be designed to withstand extreme temperatures (- 40 and 70^{o}C) and temperature cycling without leaking fuel and will be tested by a third party laboratory for verification of compliance. • (1,4) The fuel cartridge will be designed to relieve excess pressure in gases (CO) at the maximum operating design pressure level of the cartridge. • (5,6,7) The fuel cell cartridge will be designed to meet normal use and reasonable misuse, vibration, drop and crush test specifications. Transportation vibration conditions are simulated here also. • (8) Fuel cartridge components/materials which are in direct contact with formic acid will be checked and tested for suitability for use with formic acid over the life of the product. • (1,2,3,4,5,6,7,8) The FAFC system will be safety certified to the **IEC 62282-6-1** Micro fuel cell standard which explicitly calls for extreme temperatures, temperature cycling, altitude change, vibration, drop, crush and critical components material qualification and compatibility with fuel tests. • Labels will be placed on the product with accompanying literature, warning against FA ingestion and contact, and exposure of cartridge to elevated temperatures over 70^{o}C (e.g., open fire.) • **Note:** Formic acid has a pungent, unpleasant smell that repels. This in itself will limit the amount that is ingested thus reducing the severity of fuel ingestion or fuel contact failure.

#	Risk Description	Risk Mitigations
2	**Formic acid leaks** out from other FAFC system components that carry formic acid fuel, such as valves or pumps, tubes and the fuel cell when subjected to the tests and conditions outlined in 1 above. leading to: - personal injury from ingestion (toxic & corrosive), skin/tissue/eye damage from contact (corrosive & toxic)	• The risk mitigations and tests outlined for the fuel cartridge will apply to other fuel carrying system components also, as deemed applicable, to qualify these other system components. • The **IEC 62282-6-1** safety standard explicitly calls for the qualification of fuel carrying components also.
3	**1. Child gains access** to the formic acid inside the cartridge or the fuel cell system and ingests the fuel. **2.** FAFC System (cartridge and fuel cell power unit) can sustain **damage under reasonable consumer use and abuse** situations such that the fuel can leak or be accessed. leading to: - personal injury from ingestion (toxic & corrosive), skin/tissue/eye damage from contact (corrosive & toxic)	• (1) Cartridge and fuel cell system components will be designed and tested to meet child resistant criteria. • (1,2) Product will be safety certified to the **IEC 62282-6-1** Micro fuel cell standard which is a consumer based safety standard. The committee developing the standard has made all efforts to ensure all anticipated use and reasonable abuse conditions are mentioned in the standard. The standard references many other consumer product safety standards, such as safety standards for consumer information technology products. • (1,2) Cartridge and fuel cell system will be designed to ensure no leak occurs as per the risk mitigations mentioned in 1 above. • (1,2) The FAFC system will be designed tamper proof, such that without special tools (e.g., screw driver, metal knife, hammer) the system cannot be taken apart and the fuel accessed.
4	**Formic acid igniting** and catching fire leading to: - personal and property damage	• Testing done in our labs showed that FA (concentrations to 94% wt.) is very difficult to ignite and does not sustain a fire. • FA (below 85% wt) from the most recent recommendations to UN is considered non-flammable. • FAFC systems under this ICAO proposal will use formic acid concentrations below 85% wt. • Product will be safety certified to the **IEC 62282-6-1** Micro fuel cell standard which explicitly states the allowable fuel concentration for use (i.e., <85%wt).

#	Risk Description	Risk Mitigations
5	**Carbon-monoxide emissions** from formic acid decomposition, may pose a CO poisoning danger to the passengers inside an aircraft cabin. OSHA Exposure limits are 25 ppm TWA (time weighted average over 8 hours a day 40 hours a week) and 200 ppm STEL (short term exposure limit = 15 minutes to a maximum of 4 times over 8 hours) . leading to: - personal injury	• FA (94% wt.) decomposes into CO at a rate of 250cc/liter/75 days at 40^{o}C. This equates to 0.334 ml of CO/200 ml fuel cartridge during a 12 hr flight. • FAFC systems will use FA (below 85% wt) that decomposes at a much slower rate than 94% FA. • Considering the lowest volume per passenger allocation in aircrafts (1m^3/passenger) and assuming no addition of fresh air (100% recirculation case), we get a CO concentration of **0.334 ppm** over 12 hours**.** Since TWA = 25 ppm for CO, **no CO buildup risk exists with 200 ml cartridges.** Note that this analysis is based on 94% wt formic acid and FAFC will use FA below 85% wt. • To challenge the TWA of 25 ppm, each passenger will need to carry 75 cartridges. • CO emissions from the FAFC system will be tested for compliance. The **IEC 62282-6-1** micro fuel safety standard explicitly calls for this emissions measurement also.
6	**Formic acid vapor emissions** challenges allowable exposure limits, caused by failure of FA vapor emissions control/containment system, leading to: people exposure (inhalation) of formic acid that challenges **5 ppm** TWA or 10 ppm STEL. leading to: - personal injury	• FA vapor emissions control/containment will be designed with sufficient safety margin and robustness to ensure nominal performance over product life. • Life time and robustness testing will be done to qualify the design. • Formic acid emissions from the FAFC system will be tested for compliance. The **IEC 62282-6-1** micro fuel safety standard explicitly calls for this emissions measurement also. • **Note**: In the lowest volume per passenger allocation in aircrafts (1 m^3/passenger) discussed earlier and with the lowest ventilation rates for passenger comfort, 90 mg/hr of formic acid is allowed to vaporize to challenge the 5 ppm TWA level. Systems will be designed and tested to ensure emission level is below this level,
7	**Carbon-dioxide (CO_2) emissions** during operation challenges the **comfort level** in the passenger cabins of aircraft. Note: OSHA allowable exposure limits for CO_2 is 5000 ppm TWA and 30,000 ppm STEL. leading to: - personal injury	• CO_2 emissions will be quantified over the product lifetime and its effects on the TWA exposure limits and the aircraft comfort level evaluated. • CO_2 emissions from the FAFC system will be tested for compliance. The **IEC 62282-6-1** micro fuel safety standard explicitly calls for this emissions measurement also. • Labels will be placed on the product and wording included in accompanying literature, instructing the user of the CO_2 emissions and recommending use in well ventilated areas or CO_2 monitored and controlled areas.

#	Risk Description	Risk Mitigations
8	Formic acid produces **Hydrogen (H_2) gas** at temperatures above 150°C or at lower temperatures but in the presence of a catalyst (as is the case during operation or possible fuel cell failure situations). leading to: - personal injury or equipment loss from hydrogen fire or explosion.	• In the lowest volume per passenger allocation in aircrafts (1 m^3/passenger) and with 100% recirculation over 12 hours, a buildup of H_2 to 25% of LFL (1% H_2 by volume in 1 m^3) allows a H_2 emissions rate of **14 ml/min** per FAFC system. Design will meet and exceed this specification for all conditions of operation. This will ensure no H_2 buildup can occur. • Pure hydrogen exhausted at 3 ml/min from a hole that is mechanically not a flame quencher and in ideal wind conditions will result in a standing flame. Design will be done and qualified to ensure that under all conditions, the hydrogen generated and exhausted is less than 3 ml/min. Since the hydrogen emission is mixed with CO_2 exhaust, a standing flame will not be possible at the exit. • FAFC uses a PEM membrane which allows the use of any hydrogen produced to generate electricity. • Temperatures above 104°C are practically not possible in FAFC systems because formic acid boils and vaporizes at 104°C. Also, FAFC system temperature is monitored and triggers a high temperature shutdown of the system at 90°C. • Also, FAFC systems nominally operate at a maximum temperature that is 30°C above ambient. • **IEC 62282-6-1** Micro Fuel Cell Safety standard explicitly calls for hydrogen emissions testing also.
9	Formic acid produces **Formaldehyde** at temperatures above 300°C. leading to: - personal injury from exposure to formaldehyde	• Under normal operating conditions, average temperatures seen in the fuel cell will be 10 to 30°C above room temperature. • Temperature sensors in the fuel cell will abort fuel cell operation if temperature runaway (> 90°C) events were to occur. • FAFC systems cannot practically exceed 104°C (see reasons cited in 8 above) • The FA containment system will contain any transient formaldehyde formation internally. • **IEC 62282-6-1** Micro Fuel Cell Safety standard also cites and explains formaldehyde emissions in FAFC systems.

#	Risk Description	Risk Mitigations
10	Operation of the FAFC system may cause **oxygen depletion** to below 18% levels (considered unsafe threshold for humans) and challenges the comfort levels in passenger cabins in aircraft. leading to: - personal injury from oxygen depletion.	• **Note:** In the FAFC system, O_2 depletion and CO_2 emission hazards are directly related to each other from the pure chemical reaction point of view. **$HCOOH + 1/2O_2 \rightarrow H_20 + CO_2$** • From the equation, O_2 consumption is at half the rate of CO_2 production. Since the O_2 level has to fall from 20.9% to 18% (a 3% drop) and the CO_2 has to rise to 0.5% (a 0.5% rise), the CO_2 problem will occur first. This makes the CO_2 production a more prevalent risk in the aircraft cabin than the O_2 depletion. • If adequate ventilation exists and the CO_2 level is at acceptable levels, then the O_2 depletion will not be an issue. • Labels will be placed on the product or included in accompanying literature, instructing the user that the system consumes oxygen while in operation and that the device should be used in adequately ventilated areas. • **IEC 62282-6-1** Micro Fuel Cell Safety standard also cites and explains oxygen depletion in FAFC systems. The standard calls for labeling that mentions the requirement of adequately ventilated areas.
11	**Product flammability hazard -** materials coupled with fuel vapor production, ignition sources, and electrical heat may cause fires.	• Materials of components which are in direct contact with FA will not support a flame. • FA concentrations of 85% wt and less are not flammable. Note: FAFC system will use FA concentrations of 85% wt or less. • Auto ignition temperature of pure FA is 539°C. • All electronics in the fuel cell system will be non-arcing and non-sparking. • Control system monitors current draw and will trigger system shut down on an over-current situation. • Response of system to short circuit testing will be verified. • Flame retardant material is required for many of components in the FAFC system as per the **IEC 62282-6-1.** • **IEC 62282-6-1** standard calls for short circuit testing and checks for flammability rating of materials used in the construction of the device. • Labels will be placed on the product or included with accompanying literature, warning against exposing FAFC system to open fire.

#	Risk Description	Risk Mitigations
12	**Long term storage** of system (fuel cell power unit and fuel cartridge) or cartridge at elevated temperatures can lead to **buildup of CO** in confined air tight spaces leading to: - personal injury from exposure to CO.	• Labels will be placed on the product or included with accompanying literature, warning against storage in confined spaces and at elevated temperatures for long periods of time. • Instructions will be included in accompanying literature advising that packaging of bulk quantities of cartridges or systems should be done in non air tight packages. • Carbon monoxide emissions risk mitigations, mentioned in risk # 5 earlier, apply here also. • **IEC 62282-6-1** standard calls for long term storage testing for FAFC cartridges.
13	**All anticipated failures in the technology not assessed** and tested for during certification at the third party test labs.	• **IEC 62282-6-1** standard explicitly calls for a **FMEA (Failure Modes & Effects Analysis)** to be conducted by the manufacturer and presented to the test lab as part of the certification requirements. The contents of the FMEA will be similar to this risk analysis document but more detailed in the description of the cause of the failure and the design controls put in place to combat the failure. Third party labs will use the FMEA to ensure all aspects of the design that are safety critical are qualified.

SUMMARY OF THE FAFC DESIGN FEATURES FOR RISK MITIGATION

The risk analysis section, described above, describes the level of due diligence that FAFC systems developers are committing to. This will ensure that consumer products released into the market place are safe. The following section summarizes the safety related design safety features of the FAFC system.

FUEL FEATURES

The fuel used in FAFC systems is less than 85% formic acid by weight concentration. This makes the fuel non-flammable (flashpoint > 65^{o}C) and less susceptible to CO decomposition. Also, formic acid has a strong pungent smell thus making it very unattractive to ingest or to come in contact with when leaked.

FUEL CARTRIDGE FEATURES

The fuel cartridge size is limited to 200 milliliters. This ensures access is limited to a restricted quantity of formic acid in case of exposure of cartridge to conditions above design and test specifications. The cartridge is designed to extremely stringent specifications of temperature, differential pressure, vibration, drop, crush, child resistance, tamper proof, and material compatibility to fuel to ensure no leakage occurs in all foreseeable use and reasonable abuse and consumer transportation scenarios. The cartridge will be built out of material that will ensure all safety measures are achieved. The connector will only allow fuel flow when mated with the proper mating connector as is the case when connected to the fuel cell power unit. Upon disconnecting the cartridge from the fuel cell power unit, the connector seals shut and stops fuel flow immediately.

FUEL CELL POWER UNIT FEATURES

The fuel cell power unit will be designed to the same stringent requirements as the cartridge and will be tested similarly. The fuel that is present in the fuel cell power unit during operation is less than 10 milliliters and after shutdown the residual fuel is less than ten percent of that amount.

FAFC SYSTEM FEATURES

The FAFC system is designed with smart control electronics that monitor the FAFC system parameters and will trigger system shutdown (via shutting flow of fuel to the fuel cell power unit) when safety critical failures, such as high temperature, excess current draw, and unrecoverable voltage drop, occurs. This will ensure the termination of failures (e.g., large loads or internal short-circuits in the power control system) during the initial stages such that fires and extremely high temperature hazards do not occur. The control electronic will be designed and tested to consumer electronics levels of electromagnetic compatibility (EMC) specifications to ensure reliable operation of the safety control systems. Where applicable, appropriate component certification activities will be linked to the control system validation and qualification.

EFFLUENTS CONTAINMENT AND CONTROLS

The FAFC system during operation, both in normal and abnormal conditions, may theoretically produce gas effluents such as carbon dioxide, carbon monoxide, formic acid, formaldehyde and hydrogen. Apart from carbon dioxide emissions risks, risks associated with the last four effluents (CO, FA, formaldehyde, and hydrogen) are minimal based on the rare conditions needed to generate the effluents and the small amounts of the effluents that are produced. The carbon dioxide issue is dealt with written warnings and labels on the product or instructions informing the user to operate the systems in well ventilated or carbon dioxide monitored spaces.

TESTING PROTOCOLS AND QUALIFICATION

The risk/safety analysis section also described in great detail the testing and qualification protocol that will be implemented to ensure appropriate due diligence is done. The product will be certified to IEC 62282-6-1 Micro Fuel Cell safety standard by a third party test laboratory such as Underwriter's Laboratory (UL) and/or Canadian Standards Association International (CSA). The safety standard specifies requirements and provides guidelines for evaluating the safety of the product which parallels the requirements for risk mitigation discussed in the risk analysis section of this document.

THIRD PARTY LABORATORY TESTING

The independent third party test laboratory mentioned in the earlier parts of the document is referring to the equivalent of Underwriter's Laboratory (UL) and/or Canadian Standards Association International (CSA). Such test facilities have been in the independent product testing and certification business for many years and have also acquired valuable testing and safety evaluation experience with fuel cells in the last ten years. These testing facilities also have many years of experience in cross referencing other appropriate safety standards for refining or adding requirements when the need arises. The basis of their product testing and certification issuing is qualification of the existence of sufficient safety and non-existence of unacceptable risks during the product lifetime.

— END —

ICAO Member Briefing

Passenger and Crew Exception for Fuel Cells Powered by Hydrogen stored in Metal Hydrides

July 28, 2005

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1. Introduction

Growing demand for more powerful portable communications and computing devices is pushing battery capabilities well beyond their capabilities. Fuel Cell technology is emerging as a strong candidate to replace batteries in these portable applications, offering benefits including longer run times, very fast recharging and better lifecycle performance than even the most advanced battery chemistries. All fuel cells operate on the same basic electrochemical principles; they can be powered with different fuels, each with distinct attributes. The major developers of micro fuel cells have been working with the US Fuel Cells Council and the International Electro-technical Commission to develop standards of safety for these devices, no matter what fuel is used. The industry objective is to ensure they deliver enhanced user functionality while maintaining the highest standard of safety.

This white paper provides a background briefing and risk analysis in support of the United States Fuel Cell Council (USFCC) proposal to ICAO asking for an exception to allow micro fuel cell power systems and cartridges on board passenger aircraft. This paper specifically addresses fuel cells powered by hydrogen stored in metal hydrides. We provide an overview of the technology and an assessment of potential risks and mitigation strategies associated with the technology.

2. Technical Description

Micro fuel cells powered by hydrogen stored in metal hydrides provide a simple, almost 'solid state' system for producing electrical power. The hydrogen in these systems is largely trapped in a metal matrix, so the volume of gaseous hydrogen enclosed within the system at any time is extremely low. This low operational volume combined with the non-toxic nature of hydrogen and its very rapid diffusion properties make these systems both robust and safe. The technology is in many ways equivalent to PEM fuel cell technology being developed for larger format stationary and automotive power plants and so represents an important new capability that will be emerging in numerous industrial and consumer applications in the coming years. Micro fuel cells based on hydrogen represent the first wave of these new technologies that will demonstrate the safe distribution, storage and use of hydrogen with guaranteed zero emissions.

There are four basic components required to make a micro fuel cell operate using hydrogen, as shown in Figure 1. The metal hydride storage system provides a low pressure means of capturing and holding on to hydrogen, releasing it at a slow rate that is self-regulating. Hydrogen gas at low pressure flows into the hydrogen fuel cell anode chamber, while the cathode is exposed to the ambient environment so that electrical potential is produced and fed into the electrical power conditioning circuit, which regulates the power to a suitable level to drive the electronic device to which the system is coupled.

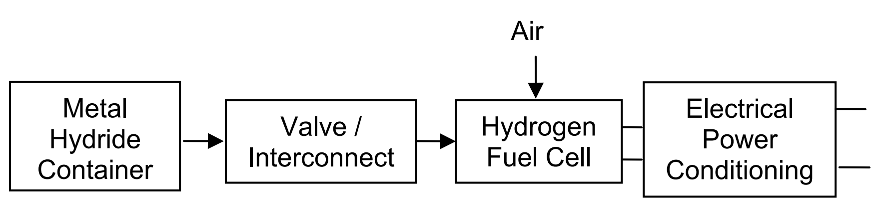

Figure 1: System Block Diagram

Figure 2 shows a cross-sectional schematic of a hydrogen powered micro fuel cell. While only a single cell is shown, multiple cells are typically configured into a structure with suitable voltage and current characteristics to power an electronic device. Hydrogen diffuses off the hydride material at low pressure and into the anode chamber, where it is consumed at the anodes with no leakage or emissions. Air from the ambient environment is consumed at the cathodes, where a small amount of product water is produced in vapour form. There are no other emissions during operation.

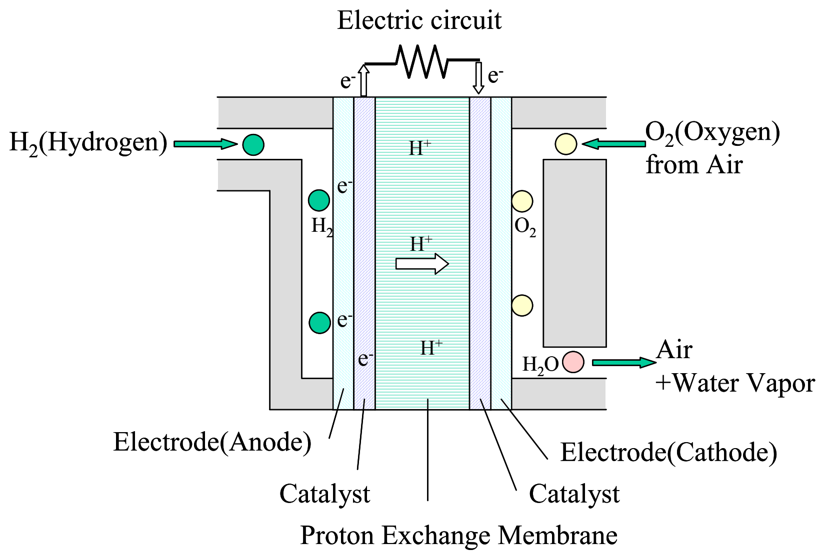

Figure 2: Ambient Air Breathing Fuel Cell Operation. Hydrogen is held in closed plenum

The coupling of the fuel cell with metal hydride hydrogen storage achieves overall system simplicity that is attractive in portable applications. Metal hydrides provide on-board hydrogen storage by bonding hydrogen molecules directly to the surface of the hydride material. The hydride is 'charged' by subjecting the hydride to an elevated hydrogen pressure, whereupon the bonding occurs. The amount of hydrogen that can be stored in any given volume of metal hydride actually exceeds the amount of liquid hydrogen that could fill the volume, but the metal hydride provides the huge advantage of operating at ambient temperatures with overall pressures limited to one or two atmospheres. In operation, hydrogen desorbs from the metal hydrides in a self regulating fashion, i.e. hydrogen desorbs until the system achieves a 'plateau pressure'; once this pressure is achieved, the hydrogen stops desorbing from the hydride. As a result, the rate of desorption becomes linked to the rate of hydrogen consumption on the anodes of the fuel cell. This coupling provides a stable hydrogen production system that minimizes the amount of gaseous hydrogen present in the system at any given time.

Metal hydrides suitable for use in micro fuel cell systems typically operate at pressures below 30 psi. The majority of hydride materials being developed for product application have no self-heating characteristics and can be exposed to air without any major safety concerns. Figure 3 shows some examples of small hydride tanks to be used in portable applications.

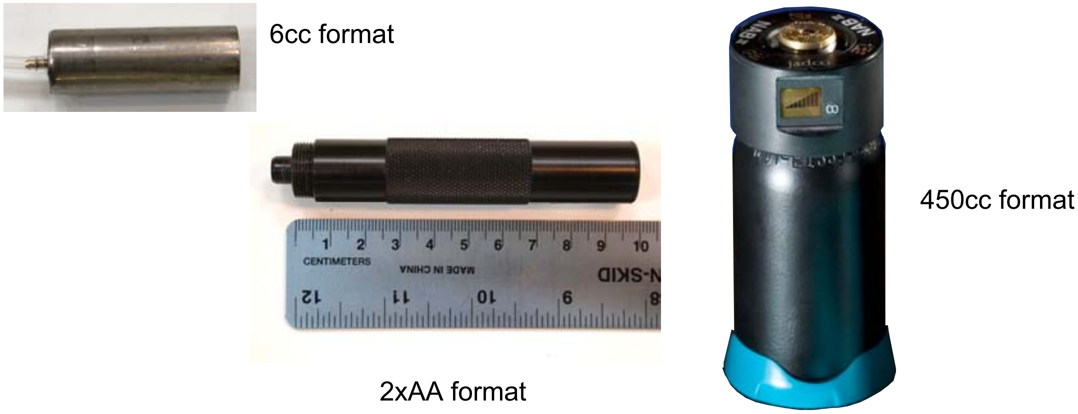

Figure 3: Small format metal hydride tanks for portable electronics applications[1]

Hydrogen gas can be shipped as a hazardous material by ground, rail, cargo vessel, or on cargo aircraft only under the UN number 1049 as a class 2.1 material. In the United States, there is a limited quantity exception[2] for containers with less than 120mL volumetric capacity, which provides freedom from all packaging regulations when shipped by cargo aircraft, and from both packaging and labeling requirements when shipped by ground. These containers may also be shipped as a consumer commodity, allowing up to 30kg of these containers to be shipped commercially in a single outer package. The level of risk associated with such small containers is inherently low; as such, it is appropriate to allow manufacturers to ensure simply that their products will safely contain the hydrogen gas, without being subject to additional packaging requirements.

Hydrogen absorbed in reversible metal hydrides is a newly regulated dangerous good, classified under UN 3468 as a class 2.1 material. The current packing instruction simply states that packaging must be approved by the governing state prior to shipment. Several such approvals have been issued by the US DOT in the form of exemptions, including one for transport of up to 200 lbs of hydride by cargo air. In January 2005, the DOT added packing instruction 49 CFR §173.214 to the UN 3468 entry, allowing for shipment once approved by the Associate Administrator (instead of requiring an exemption). The first DOT Approval of this nature is in progress and should be issued in the next month for shipment via cargo aircraft.

In April 2005, ICAO approved the inclusion of Special Provision A2 for hydrogen in metal hydrides which allows international shipment upon receipt of approval from the State of Origin.

The US Department of Transportation, in cooperation with industry representatives from both Canada and Japan, is preparing a draft packing instruction to allow transport of hydrogen in metal hydride by cargo aircraft only. This packing instruction proposal will be presented to ICAO in October 2005 and will allow hydrogen in metal hydride storage systems to be shipped without need for special permission from the relevant governing authority. In addition, the proposal includes the addition of Special Provision A1 to the entry in the ICAO Technical Instructions, which would allow transport of such materials on passenger aircraft if permission were granted by the appropriate governing authority.

[1] 6cc and 2xAA format photos courtesy Angstrom Power Inc; 450cc format photo courtesy Jadoo Power Systems, Inc. All photos copyright.

[2] 49 CFR § 173.306, Limited quantity exception for flammable gas, <4 fl oz containers are excepted from packaging requirements in strong outer packaging with up to 30kg total in one package.

One major benefit of using hydrogen stored in metal hydrides is the vast expanse of research and development that has been conducted on this technology suite during the past 30 years. Metal hydrides are safely used in batteries as well as in solid state air conditioning systems with very good effect. Furthermore, because research in fuel cells at larger power levels is so intense, it is reasonable to expect steady improvement in safety and performance as the technology matures further.

In small systems suitable for powering handheld electronics devices such as cell phones operation can be sustained with entirely closed off hydrogen chambers and no control system. Hydrogen powered portable devices, such as those shown in Figure 4, provide convenient portable power with no moving parts, no electronic controls and no emissions during operation.

Figure 4: Hydrogen Powered portable electronics devices. Left: Outboard Charging devices, Middle: Fuel Cell Powered flashlight Right: Professional Video Camera Power Supply[3]

[3] Outboard charging device photos courtesy Nippon Telegraph and Telephone Corporation and Angstrom Power Inc; Fuel Cell Powered flashlight photo courtesy Angstrom Power Inc; Professional Video Camera Power Supply photo courtesy Jadoo Power Systems Inc. All photos copyright.

Appendix A. Risk Analysis

Fuel Cells powered by hydrogen stored in metal hydrides are subject to safety testing associated with the proposed IEC 62282-6-1 and draft ISO 16111 standards. A summary of the type test requirements for fuel cell systems powered by hydrogen stored in metal hydride is included in Appendix A.

A risk and safety analysis performed on fuel cells powered by hydrogen stored in metal hydrides highlights various product design controls and qualification testing activities to prevent safety critical failures and eliminate unacceptable risks. The table below summarizes the potential risks and associated mitigations that can be demonstrated through physical analysis and/or testing to assure safety thought the life of the product. Note: Bracketed numbers the “Risk Mitigations” column indicate corresponding numbered items in the “Risk Description” column.

#	Risk Description	Risk Mitigations
1	**Hydrogen is released** by the metal hydride cartridge from exposure to: **1. High temperature** (70°C) for 4 hours **2. Low temperature** (-40°C) for 4 hours **3. Temperature cycling** between -40°C and 55°C **4. Altitude change** in aircraft transportation (equivalent to 95 kPa below standard atmospheric pressure for 30 minutes @ 20°C) **5. Vibration** (sinusoidal 7Hz - 200Hz, 1gn -8gn) **6. Dropping** (from 1.8 m height as per transportation requirements and instructions) **7. Crushing** of cartridge (100 kg mass) **8. Cartridge components/material degradation** failure during life time of the product **9. Exposure to fire** **10. Impacts on the delivery valve** leading to: - A fire or explosion hazard. - Personal injury from asphyxiation. - Personal injury for projectiles released from a cartridge rupture.	• (1,4) The fuel cartridge will be designed and tested to withstand 2 times the working pressure at 55°C. • (1,2,3) The fuel cartridge will be designed to withstand extreme temperatures (- 40 and 70°C) and temperature cycling without leaking fuel. • (1,4,9) The fuel cartridge will be designed to relieve excess gas pressure above the maximum operating pressure in a safe controlled manner, even in the case of exposure to fire. • (5,6,7) The fuel cartridge will be designed and tested to demonstrate its ability to withstand normal use and reasonable abuse due to vibration, drop and crushing forces. • (8) Fuel cartridge components/materials in direct contact with hydrogen will be proven suitable for use with hydrogen over the life of the product through testing. • (1,2,3,4,5,6,7,8,9) The cartridge will be safety certified to the IEC Micro Fuel Cell Standard which explicitly calls for tests in extreme temperatures, temperature cycling, high temperature long term storage, altitude change, vibration, drop, crush and critical components material qualification and compatibility with fuel tests. Testing will be by a third party laboratory for verification of compliance. • (1,2,3,4,5,6,7,8,9,10) The nature of the metal hydride material will ensure that the hydrogen can only be released slowly as it desorbs rather than all at once. Due to the highly endothermic nature of hydrogen desorption from the metal hydride, full desorption of a ruptured cartridge would take 20 – 200 min or even longer, depending on cartridge design and hydride type. • (1,2,3,4,5,6,7,8,9,10) The rapid rate at which

		hydrogen diffuses in air limits the time during which a hydrogen release poses a threat. • (1,2,3,4,5,6,7,8,9,10) The cartridge will be designed and tested to demonstrate that high speed projectiles are not produced in the case of a rupture, even in the case of exposure to fire. • Labels will be placed on the cartridge with accompanying literature, warning against tampering, exposure to children, and exposure to elevated temperatures over 55°C (e.g., open fire.) • Cartridges will be made in accordance with ISO 16111 which limits the leak rate to 1 standard cubic centimeter per hour under normal operating conditions as well as after type test requirements. • (10) The cartridge valve shall be impact tested in accordance with the valve impact test of ISO 16111.
2	**Hydrogen is released** by the fuel cell system from exposure to: **1. High temperature** (55°C) for 4 hours **2. Low temperature** (-40°C) for 4 hours **3. Temperature cycling** between -40°C and 55°C **4. Altitude change** in aircraft transportation (equivalent to 33 kPa below standard atmospheric pressure for 6 hours and 95 kPa below standard atmospheric pressure for 30 minutes @ 20°C) **5. Vibration** (sinusoidal 7Hz - 200Hz, 1gn -8gn) **6. Dropping** (from 1.2 m height as per transportation requirements and instructions) **7. Crushing** of the fuel cell system (25 kg mass) **8**. **Cartridge components/material degradation** failure during life time of the product leading to: - A fire or explosion hazard. - Personal injury from asphyxiation. - Personal injury for projectiles released from a fuel cell system rupture.	• (1,4) The fuel cell system will be designed and tested to withstand 2 times the working pressure at 55°C. • (1,2,3) The fuel cell system will be designed to withstand extreme temperatures (- 40 and 55°C) and temperature cycling without leaking fuel. • (1,4) The fuel cell system will be designed to relieve excess gas pressure above the maximum operating pressure in a safe controlled manner. • (5,6,7) The fuel cell system will be designed and tested to demonstrate its ability to withstand normal use and reasonable abuse due to vibration, drop and crushing forces. • (8) Fuel cell system components/materials in direct contact with hydrogen will be checked and tested for suitability for use with hydrogen over the life of the product through testing. • (1,2,3,4,5,6,7,8) The cell system will be safety certified to the IEC Micro fuel cell standard which explicitly calls for extreme temperatures, temperature cycling, high temperature long term storage, altitude change, vibration, drop, crush and critical components material qualification and compatibility with fuel tests. Testing will be by a third party laboratory for verification of compliance. • (1,2,3,4,5,6,7,8) The nature of the metal hydride material will ensure that the hydrogen can only be released slowly as it desorbs rather than all at once. Due to the highly endothermic nature of hydrogen desorption from the metal hydride, full desorption of a ruptured fuel cell system would take 20 – 200 min or even longer, depending on cartridge design and hydride type. • (1,2,3,4,5,6,7,8) The rapid rate at which hydrogen

		diffuses in air limits the time during which a hydrogen release poses a threat. • (1,2,3,4,5,6,7,8) The fuel cell system will be designed and tested to demonstrate that high speed projectiles are not produced in the case of a rupture. • Labels will be placed on the fuel cell system with accompanying literature, warning against tampering, exposure to children, and exposure to elevated temperatures over 55^{o}C (e.g., open fire.)
3	**Hydrogen is released** by the fuel cell system during normal operation. leading to: - A fire or explosion hazard. - Personal injury from asphyxiation.	• The fuel cell system will be designed to limit the hydrogen emissions from any single source to 3 standard milliliters per minute. Sources of 3 ml/min or less can not sustain a flame. • The fuel cell system will be designed to limit the total hydrogen emissions from all sources such that the minimum space allocated to an aircraft passenger (1 m^3) with 10 complete air exchanges every hour would accumulate less than 1% hydrogen by volume or 25% of the lower flammable limit (LFL). • The mitigation strategies for addressing flammability address asphyxiation since 15% by volume of hydrogen is needed to reduce the oxygen concentration to 18 % by volume and this is well above the LFL for hydrogen.
4	**Hydrogen is released** while the metal hydride cartridge is connected or disconnected from the fuel cell system. leading to: - A fire or explosion hazard. - Personal injury from asphyxiation.	• The design of the fuel cell system will limit the release of hydrogen to 3 standard milliliters during either the connection or disconnection for the cartridge. This quantity of hydrogen is deemed too small to have a harmful effect. The combustion of 3 standard milliliters of hydrogen would release as much energy as 1/10 of a drop of 40% vol. liquor.
5	**Metal hydride material is released** from the cartridge and/or the fuel cell system after exposure to: **1.** The intentional actions of a consumer to compromise the integrity of the cartridge and/or fuel cell system. **2.** The cartridge and/or fuel cell system sustain **damage under reasonable consumer use and abuse** situations. **3. High temperature** **4. Low temperature** **5. Temperature cycling** **6. Altitude change** in aircraft transportation **7. Vibration**	• The metal hydride will be engineered to be have low toxicity, have negligible reactivity to water, have low flammability, and be non pyrophoric. • The nature of the metal hydride material will ensure that the hydrogen can only be released slowly as it desorbs rather than all at once. Due to the highly endothermic nature of hydrogen desorption from the metal hydride, full desorption of a ruptured fuel cell system would take 20 – 200 min depending on cartridge design and hydride type. • The mitigation strategies employed to address the risk of hydrogen leakage from the cartridge and the fuel cell system intrinsically address metal hydride leakage since a failure resulting in metal hydride leakage would also result in hydrogen leakage. • (1,2) Cartridge and fuel cell system will be safety

	8. Dropping **9. Crushing** **10. Exposure to fire** **11. Cartridge and fuel cell system components/material degradation** failure during life time of the product leading to: - ignition of flammable metal hydride material - ignition of water reactive metal hydride after exposure to water - personal injury from ingestion (potentially toxic), skin/tissue damage from contact (potential irritant) - self ignition of pyrophoric metal hydride material	certified to the IEC Micro Fuel Cell Standard which is a consumer based safety standard. • (1,2) Cartridge and fuel cell system will be designed tamper proof, such that without special tools (e.g., screw driver, metal knife, hammer) the system cannot be taken apart and the fuel accessed. • (3,6) The fuel cartridge and fuel cell system will be designed and tested to withstand 2 times the working pressure at 55^{o}C. • (3,4,5) The fuel cartridge and fuel cell system will be designed to withstand extreme temperatures (- 40 and 55^{o}C) and temperature cycling without leaking fuel and will be tested by a third party laboratory for verification of compliance. • (3,6) The fuel cartridge and fuel cell system will be designed to relieve excess gas pressure above the maximum operating pressure in a safe controlled manner. • (7,8,9) The fuel cartridge and fuel cell system will be designed to meet normal use and reasonable abuse vibration, drop and crush test specifications. • (11) Fuel cartridge and fuel cell system components/materials which are in direct contact with hydrogen will be checked and tested for suitability for use with hydrogen over the life of the product. • (3,4,5,6,7,8,9,11) The cartridge and fuel cell system will be safety certified to the IEC Micro Fuel Cell Standard which explicitly calls for extreme temperatures, temperature cycling, high temperature long term storage, altitude change, vibration, drop, crush and critical components material qualification and compatibility with fuel tests. • In addition, the fuel cartridge must meet the requirements of ISO 16111, which imposes additional, more rigorous tests on the cartridge above and beyond the IEC Micro Fuel Cell Standard's tests. For instance, fire tests and hydride expansion test will be conducted. • Labels will be placed on the cartridge and fuel cell system with accompanying literature, warning against tampering, exposure to children, and exposure to elevated temperatures over 55^{o}C (e.g., open fire.)
6	Operation of the fuel cell system may cause **oxygen depletion** to below 18% levels (considered unsafe threshold for humans) and challenges the comfort levels in passenger cabins in aircraft. leading to:	• Labels will be placed on the product or included in accompanying literature, instructing the user that the system consumes oxygen while in operation and that device should be used in adequately ventilated areas. • The fuel cell system will be design with the

	Personal injury in terms of oxygen depletion.	appropriate oxygen consumption control strategy such that the fuel cell system can operate in conjunction with a person in a 1 m^3 air volume with 10 air changes per hour without depleting oxygen levels below 18%.
7	**Product flammability hazard -** materials coupled with hydrogen release, ignition sources, and electrical heat may cause fires.	• The fuel cell system will be designed to limit the hydrogen emissions from any single source to 3 standard milliliters per minute. Sources of 3 ml/min or less can not sustain a flame. • Materials of components of the fuel cartridge and fuel cell system that may be exposed to a hydrogen leak will not support a flame. • Auto ignition temperature of hydrogen is 500^oC. • All electronics in the fuel cell system will be non-arcing and non-sparking. • A short circuit test will be conducted where the fuel cell system is short circuited for 5 minutes. During or after this time the system can not catch fire, explode, leak or reach an unacceptable surface temperature for the housing material. • Labels will be placed on the product or included with accompanying literature, warning against exposing the fuel cartridge or the fuel cell system to open fire.

Appendix B: Summary of Test Criteria

Following is an abridged list of tests associated with certification to IEC 62282-6-1 Micro Fuel Cell Safety Standard pertinent to fuel cell systems powered by hydrogen stored in metal hydrides.

IEC 62282-6-1 Test Criteria:

Differential pressure tests	- 95 kPa differential pressure applied by vacuum to the cartridge and the system or unit for 30 minutes. - Fully charged system or unit is held at 68 kPaA for 6 hours.
Vibration tests	- 7 to 200 Hz for 3 hours with acceleration of up to 8 G's applied to both the cartridge and the system or unit.
High temperature exposure tests	- 4 hours at 70°C for the cartridge.
Temperature cycling tests	- two cycles from -45°C to 55°C with 4 hour holds at the temperature extremes.
Drop tests	- from 1.2 m for the system or unit and from 1.8 m for the cartridge.
Crush tests	- 25 kg compressive load test for the system or unit and 100 kg compressive load test for the cartridge.
Short circuit tests	- system or unit is connected to a 0.1 ohm load for 5 minutes.
Exhaust gas temperature tests	- system or unit exhaust must be less than 70°C.
Long term storage tests	- cartridge is stored at 50°C for 28 days.
High temperature cartridge connection tests	- cartridge is heated to 50°C and then connected to the system or unit.
System or unit internal pressure tests	- system or unit is tested to 95 kPa above the working pressure or 2 times the working pressure, whichever is greater.

Connection Cycling tests	- 1000 cycle for the system or unit and 10 cycles for the cartridge.
Emissions tests	- emissions from the cartridge and the system or unit can not sustain a flame and can not produce 25% of LFL in 1 m^3 with 1 air change per hour.

For all of the IEC 62282-6-1 tests there is a requirement of no fire, no explosion, and "no leakage" which is defined as no leaks capable of sustaining a flame or producing 25% of LFL in 1 m3 with 1 air change per hour.

Modified ISO 16111 test criteria:

The tests apply to the cartridge and any fuel reservoirs internal to the system or unit that are separated from the fuel cell by a regulator.

Fire tests	- Cartridges exposed to fire for 20 mins. Cartridges>120 ml must remain intact throughout the test but may relieve pressure through a pressure relief device. Cartridges < 120 ml may rupture, but must do so in safe manner.
Drop tests	- 1.8 m in 4 orientations, including drop in horizontal orientation onto a steel apex for cartridges and pressurized internal reservoirs. Must pass leak test after drops with <1scch H_2 leakage.
Leak tests	- <1scch H_2 at the rated charge pressure for cartridges and pressurized internal reservoirs.
Hydrogen cycling and strain measurements tests	- At least 50 charge cycles with continuous monitoring; vibration of cartridge after each set of 50 cycles. Strain either must not exceed 50% of strain at the design pressure or show no increasing trend after 50 cycles.
Valve impact tests	- Cartridge is cooled to -40°C; valve is struck with a falling steel ball. Cartridge is then pressurized to 1.5 times the rated charging pressure and tested for leaks with < 1 scch H_2 leakage.

Risk Assessment of Micro Reformed Methanol Fuel Cells:

Safe and Advanced Portable Power for Today's Portable Device Demands

Whitepaper prepared by the International
Electrotechnical Commission (IEC) Task Group for
Reformed Methanol Fuel Cell Safety

Prepared for International Transportation
Regulators and Advisors

July 2005

Rev. 9, July 21, 2005

Table of Contents

Introduction

Methanol fuel cells offer the promise for portable power of smaller packages, longer runtimes, and the elimination of the need to recharge batteries. These systems will soon power a range of portable devices, such as laptop computers, cell phones, or PDAs, and users will want to carry these ubiquitous devices onboard commercial aircraft. Before this can happen, methanol fuel cell manufacturers must demonstrate the inherent safety of their products, and proper standards and regulations need to be set in place.

This whitepaper will address this topic for micro reformed methanol fuel cell (RMFCs), which will begin commercialization in 2006. RMFCs differ from their counterparts, direct methanol fuel cells (DMFCs), in that an RMFC will "reform" methanol fuel into hydrogen and carbon dioxide immediately before being consumed by the fuel cell.* DMFCs consume the methanol "directly," without such conversion taking place. RMFCs offer the advantage of high performance PEM fuel cells, while leveraging the simplicity and convenience of methanol fuel. From a safety and regulatory standpoint, RMFCs and DMFCs are largely the same, given that they use the same types of cartridges and fuel and employ many of the same tests. Both RMFCs and DMFCs will be subject to rigorous design type tests to demonstrate their high integrity, including the prevention of methanol leaking out due to adverse conditions that might occur during the course of their use.

This whitepaper explains how fuel cells and, specifically, RMFCs work and provides a detailed risk assessment of RMFCs. Section 1 of this document provides a basic overview of fuel cells and RMFCs. Sections 2 and 3 address specific key functions in an RMFC – outlining RMFC thermal and emissions management, respectively. Section 4 is a detailed risk assessment, covering all aspects of the RMFC, including emissions, temperatures, catalysts, and the fuel cartridge. Finally, Section 5 provides a brief summary of the international product safety standard (IEC 62282-6-1) that will be used in safety certification of RMFCs and other micro fuel cell types.

It is the recommendation of the RMFC safety task group that RMFCs and DMFCs are considered jointly as *Methanol Fuel Cells* before the ICAO Dangerous Goods Panel in October 2005 and that RMFCs are approved for use by passengers onboard commercial aircraft.

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* Note that "RMFCs" and "DMFCs" refer to micro RMFCs and micro DMFCs in this document. Both of these subtypes are covered by the IEC safety standard 62282-6-1. There are other size classes of these types of fuel cells, but these classes are not discussed in this whitepaper.

Section 1. Basics of fuel cells and RMFCs

This section provides a basic overview of the operation of RMFCs and fuel cells.

How do RMFCs work?

Figure 1 shows the basic components and processes of an RMFC: On an as-needed basis, methanol-water fuel is fed to the reformer. The reformer then converts or "reforms" the methanol to reformate, which consists of hydrogen and carbon dioxide, and this reformate is immediately consumed by the fuel cell stack. By intaking ambient air, the system produces electricity, while giving off water vapor, carbon dioxide, and unconsumed air. Additionally, the incoming air provides cooling for the system. Trace levels of other emissions are possible, but will be at low and safe levels. See Section 4 of this whitepaper for a detailed discussion of this.

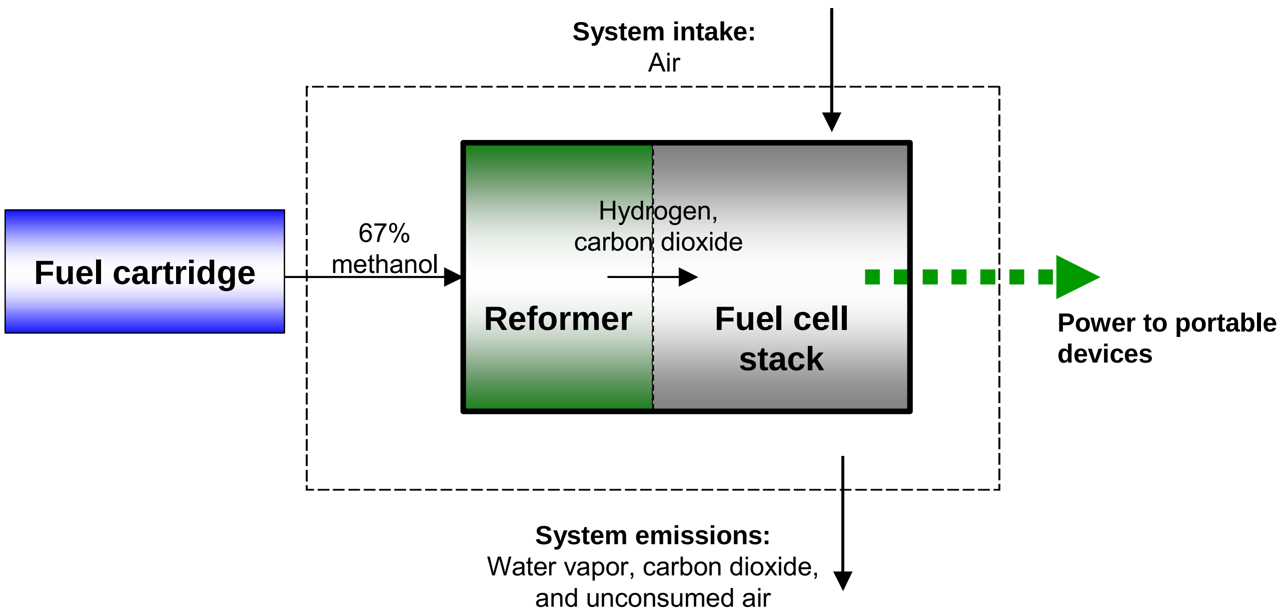

Figure 1. Basic schematic of a micro RMFC*

What is the fuel cell stack?

A fuel cell is like a battery in that it relies on chemical reactions to silently release energy in the form of electricity. However, it is also fundamentally different than a battery in how it is 'refueled': fuel cells do not need to be thrown away or undergo time-consuming recharging. Instead, they provide electricity as long as fuel is available. At the heart of any fuel cell system is the fuel cell stack, which produces the system's electricity.

* Note that the fuel in this example is 67% methanol and 33% water (by volume). In some cases, the methanol concentration is as high as 100%.

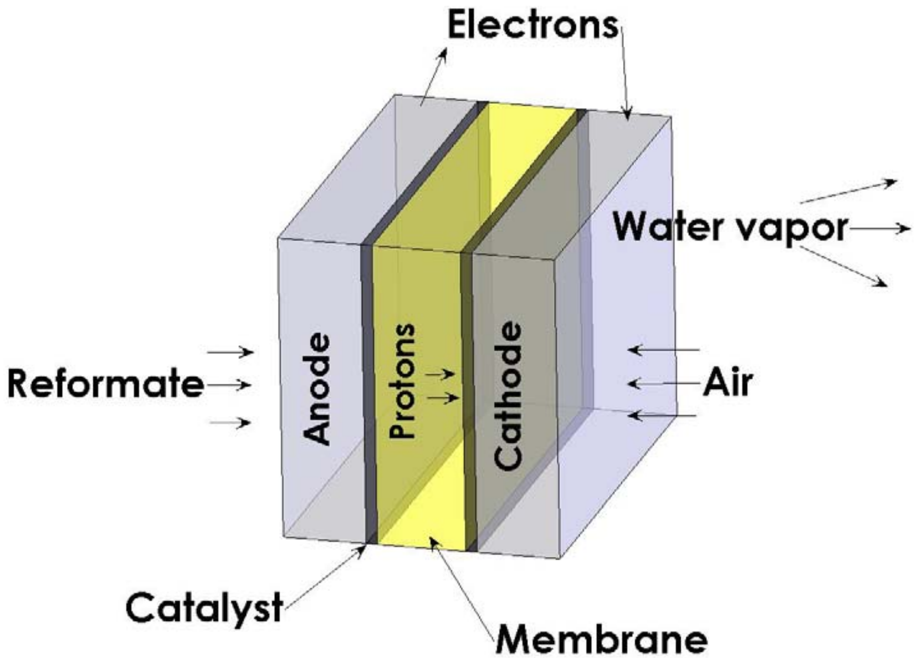

Figure 2. Diagram of a single cell

Figure 2 provides the basics of a "single cell" within a fuel cell system. In this type of fuel cell, reformate (hydrogen and carbon dioxide) is fed to one side of the fuel cell and air is fed to the opposite side. Under an electrical load, like a laptop computer, hydrogen in the reformate and oxygen in the air react to create electricity, heat, and water. These single cells are then "stacked" together as the fuel cell stack to achieve the desired operating voltage and power capabilities.

Section 2. Moderate temperature operation of micro RMFCs

This section details how micro RMFC manufacturers approach thermal management and provide an inherently safe system from the standpoint of temperature. The user of a micro RMFC experiences surface and exhaust temperatures comparable to laptop computers and other low temperature micro fuel cells. During operation, localized temperatures within the reformer and fuel cell stack are higher. However, similar to the high temperatures seen in a laptop computer processor chip, insulation and air cooling provide straightforward means of containing localized higher temperatures.

How is the end user isolated from localized high temperatures?

Figure 3 shows the liquid and gas flows in and out of a micro RMFC system. Methanol fuel and oxygen from ambient air are fed to the system, and carbon dioxide, water vapor, and unconsumed air are exhausted.

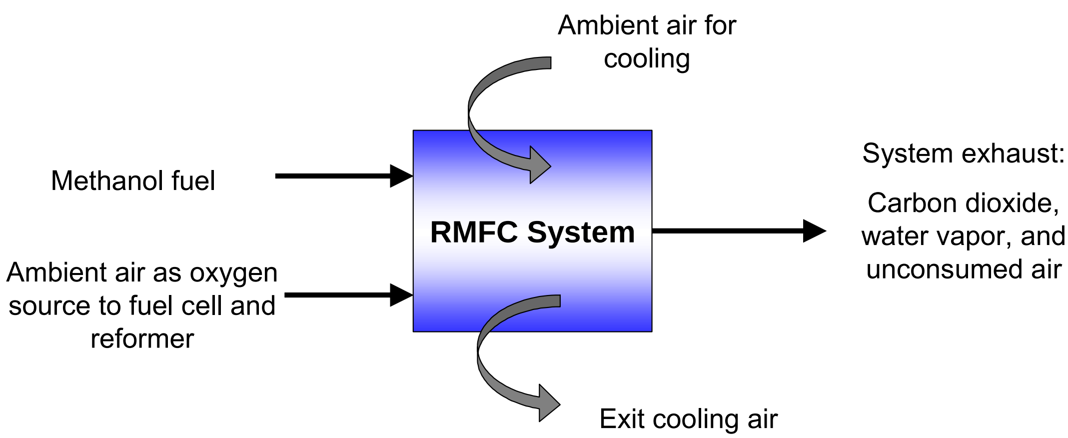

Figure 3. Liquid and gas flows in an RMFC

A detailed breakdown of the thermal management is shown in Figure 4. This schematic shows that the reformer operates at approximately 280^{o}C, and the fuel cell stack will operate in the range of 80-180^{o}C, depending upon the stack technology of choice. RMFC reformer temperatures do not exceed 300^{o}C. These localized higher temperatures are contained by layers of insulation (typically less than 0.5 in.) with the external surface of the insulation at temperatures in the range of 60-90^{o}C. These temperatures are then dropped through air cooling to 30-60^{o}C, which is the outer case temperature that the end user sees. The temperature of gases leaving the reformer at 280^{o}C is quickly dropped to 40-70^{o}C by mixing these hot gases with cooling air.

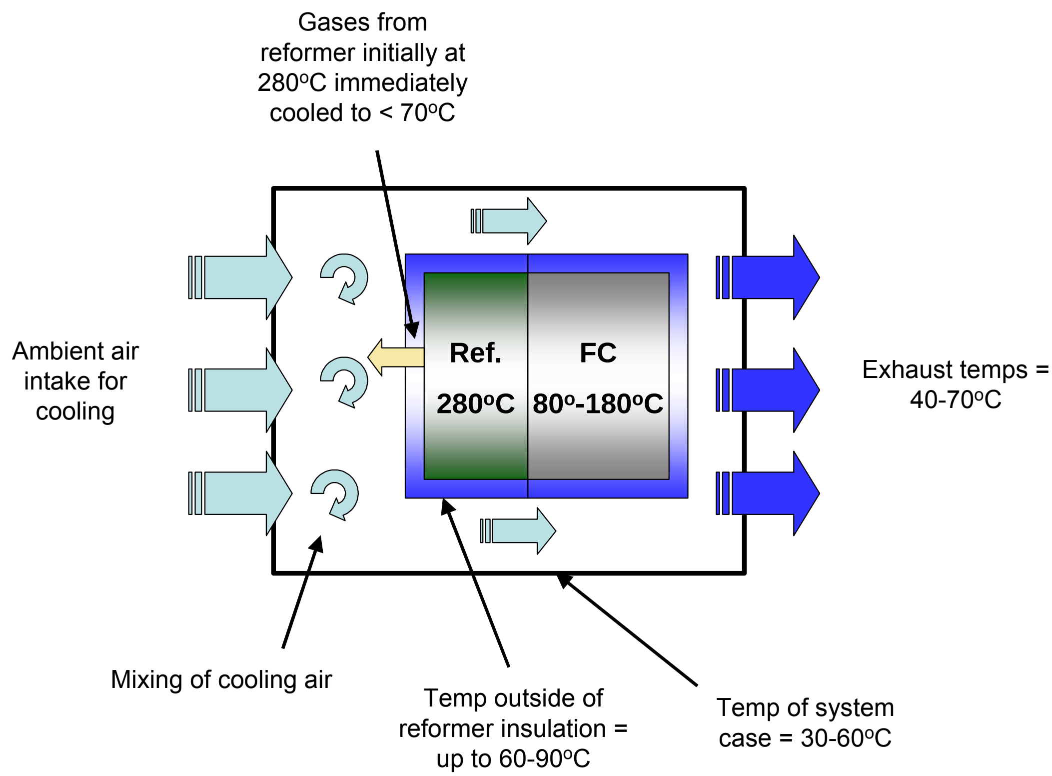

Figure 4. Thermal management in a micro RMFC

This simple and robust thermal management system shows how local higher temperatures are dropped readily with insulation layers. A variety of insulators are well known that can provide these temperature drops.[1] Isolating these local high temperatures is therefore a straightforward task with available insulators. The main thermal management challenge is thus removing the inherent heat generated in any micro fuel cell. The following evaluation shows how micro RMFCs fundamentally and safely address this.

How much heat do RMFCs give off?

Ultimately, the challenge of thermal management is dominated by the amount of heat produced by the system.[*] Figure 5 shows how much heat would be generated by a typical RMFC used to power laptop computers.[**] This graphic shows that the amount of heat produced for a given application is only dependent upon the net efficiency: the higher the efficiency, the lower the amount of waste heat generated. In this scenario, 47 W of heat must be removed to prevent overheating. For a laptop micro fuel cell that runs at an efficiency below 30%, more than 47 W would need to be removed, and the thermal management task would become a more difficult one.

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[*] *Temperature* is defined as the degree of hotness or coldness of a body or environment, whereas *heat* is defined as a form of energy that is transferred by a difference in temperature.
[**] Note that micro fuel cells can have a range of efficiencies. 30% net efficiency is representative of many laptop RMFCs and is a best case scenario for laptop DMFCs. Across all micro fuel cell applications, DMFCs can realistically have efficiencies of 15-30%, and RMFCs can have efficiencies of 20-35%. (Source: Motorola, Casio, UltraCell)

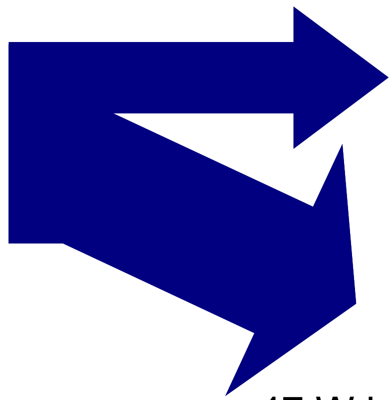

Figure 5. Energy flows for a 20 W RMFC and DMFC systems running at equivalent net efficiencies

What safety redundancies are used to ensure moderate temperatures?

Any consumer device that produces heat can overheat given the necessary abuse. Thus, micro fuel cells incorporate the redundant safety features to ensure overheating does not occur. Equipped with multiple temperature sensors, the micro RMFC system will shut off immediately at above normal temperatures, similar to appliances such as coffee makers. The risk assessment in Section 4 provides further detail on this.

Thermal management summary

Micro RMFCs thus provide high levels of thermal safety. Insulation of localized high internal temperatures safely reduces the temperatures experienced by the user. High efficiencies minimize the challenges of heat management. Finally, proven redundant thermal safety mechanisms protect against any abnormally high temperatures from system abuse.

Section 3. Emissions safety

This section addresses the question of emissions from an RMFC. Unwanted emissions have the potential to exist in all methanol fuel cells. RMFC manufacturers resolve this through the use of a catalytic heater, which safely and fully converts unwanted emissions – including hydrogen and methanol – to carbon dioxide and water.

What is the catalytic heater and how does it ensure safe emissions?

Figure 6 details the gas and liquid flows in the various parts of an RMFC. The entire reformer unit (sometimes called the "fuel processor") is subdivided into two sections. The "reformer" coverts or reforms the methanol to hydrogen reformate. The "catalytic heater" is the other chamber designed to ensure safe emissions and help keep the system warm, especially during system start-up.

The catalytic heater is an inherently robust solution to any unwanted emissions. All system gases pass through it before exiting the system, and it efficiently converts any potential intermediates to carbon dioxide and water. These potential intermediate include methanol, hydrogen, and carbon monoxide, as well as possible trace amounts of formic acid and formaldehyde.[2] The RMFC design, thus, removes unwanted emissions through its catalytic heater by converting these emissions to harmless water vapor and carbon dioxide.*

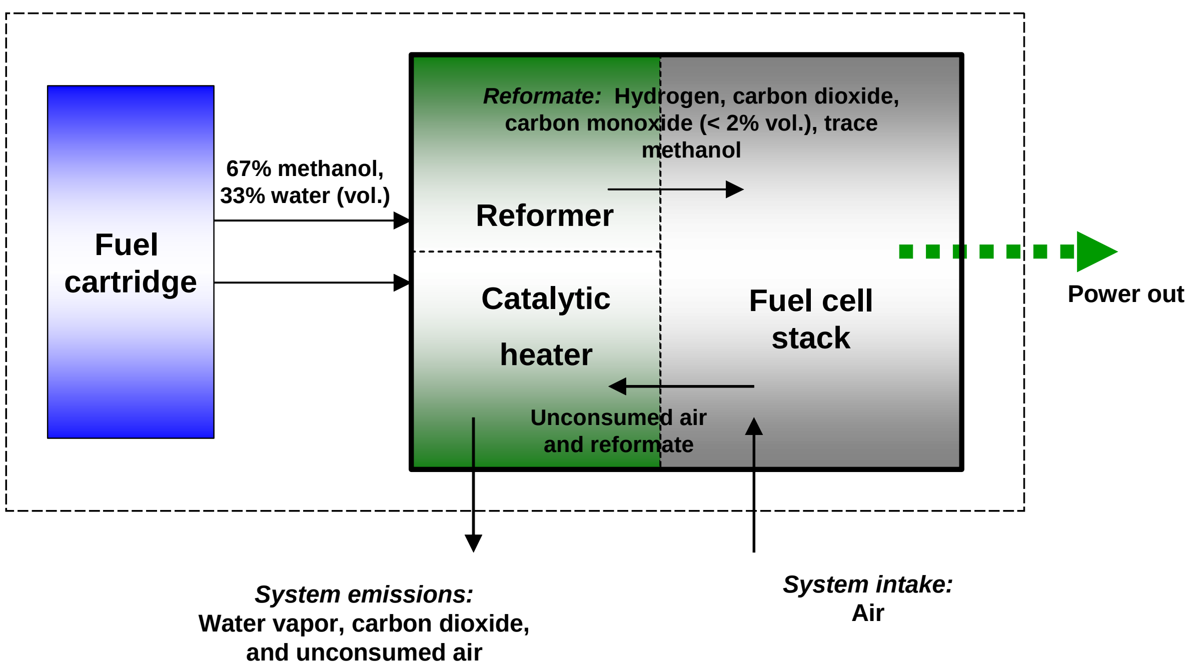

Figure 6. Detail of gas and liquid flows in RMFCs

* Two RMFC systems for laptop computers (20-25 Watt each) will produce carbon dioxide levels approximately equivalent to the level exhaled by an adult human.

Are there hydrogen emissions?

The hydrogen within the system is produced “on demand” and is consumed immediately by the fuel cell stack and the catalytic heater. Thus, the hydrogen is fully consumed inside the system.

The IEC safety standard 62282-6-1 requires that the hydrogen emission rate is maintained at a very low level – less than 3 cc/min from a single source. This level was chosen because, under all circumstances, it is impossible for emitted gas to support a flame. Additionally, IEC testing requires that emissions concentrations never exceed 25% of the lower flammability limit (LFL).

Further, the amount of hydrogen in the system is very low, being equivalent to the energy in less than 1/10 of one drop of alcohol (assuming a drop weighs 0.025 g). It is therefore not a product of the system, but rather a process intermediate that is immediately consumed within the system. Fuel pumping capabilities also ensure that there is a low ceiling on how much hydrogen can be made: a pump going at its maximum rate still leads very low hydrogen production rates. Finally, if there is a small leak, the system will immediately detect this and automatically shutdown.

Emissions safety summary

Safe emissions from RMFCs are therefore addressed through the catalytic heater, low amounts of hydrogen within the system, automatic shutdown, and low ceilings on maximum hydrogen generation rates. This high efficiency component ensures that all gas streams are converted to carbon dioxide and water vapor before exiting the system. Section 4 provides further details on emissions safety.

Section 4. Risk assessment of RMFCs

Risk to address	Risk mitigation
1. How are risks of system overheating addressed?	1. The system is designed and tested to monitor temperature through redundant temperature sensors, and the system will shut down if there is any instance of overheating. This is done through the use of the system's microcontroller, which controls the system functions and will shutoff fuel and air delivery upon sensing an unacceptable high temperature. Temperatures will decrease with fuel and air shutoff. 2. The microcontroller will also physically disconnect the fuel cartridge from system if there is system overheating. 3. Microcontroller failure automatically causes the fuel to shutoff. 4. High temperature zones are reliably insulated and isolated from the rest of the system and user. The fuel cartridge is a separate unit. Temperatures on the outside of the insulation surrounding the reformer unit and the catalytic heater are kept at 60-90^{o}C during normal operation. 5. Excess cooling air flow capacity provides cooling to maintain a safe operating temperature. Product enclosure temperatures are less than 60^{o}C, and system exhaust temperatures are less than 70^{o}C. 6. The system is designed and tested to operate safely at 30^{o}C above the normal maximum operating temperature through high temperature materials and construction. At this elevated temperature, the user will not experience high temperatures (product enclosure temperature will remain less than 60^{o}C, exhaust temperature will remain less than 70^{o}C). 7. High efficiency operation of RMFCs reduces the amount of heat that must be removed from the system. Net efficiencies are typically around 30%.
2. How are risks of user exposure to high temperature mitigated?	The analysis 2.1 above applies here as well.
3. The catalytic heater is an important component in removing hydrogen and other flammable gas emissions. What is done to mitigate the risk of its failure?	1. The catalytic heater contains no moving parts, thereby making failure unlikely. 2. If a failure were to occur, the loss in catalytic heating capability will cause immediate cooling and system shutdown. Temperatures are continuously monitored through redundant temperature sensors, and the system will shutdown under these conditions. The system's microcontroller controls the system functions and will shutoff fuel and air delivery. 3. The microcontroller will also physically disconnect the fuel cartridge from system if there is abnormal system cooling from catalytic heater failure. 4. Microcontroller failure automatically causes the fuel to shutoff. 5. System cooling will cause significant loss in hydrogen production abilities.

4. What is done to address the risk of a hydrogen reformate leak?	1. If a leak were to occur, the catalytic heater would see abnormally low amounts of hydrogen. This would cause immediate cooling and safe system shutdown. Temperature is continuously monitored through redundant temperature sensors, and the system will shutdown under these conditions. The system's microcontroller controls the system functions and will shutoff fuel and air delivery. 2. The microcontroller will also physically disconnect the fuel cartridge from system if there is system cooling from a leak failure. 3. Microcontroller failure automatically causes the fuel to shutoff. 4. System cooling such as this will cause significant loss in hydrogen production abilities. 5. The loss in hydrogen reformate would cause an immediate drop in fuel cell stack voltage, thereby initiating safe system shutdown.
5. If fuel delivery to the reformer is too high, excess hydrogen will be generated. Possible reasons for such failure include poor calibration and a valve failing to close. What is done to mitigate this risk?	1. If too much hydrogen reformate is fed to the system, the catalytic heater will consume this reformate, the system will immediately heat up and will safely shut down. Temperature is continuously monitored through redundant temperature sensors and shuts down with any overheating. The system's microcontroller controls the system functions and will shutoff fuel and air delivery. 2. The microcontroller will also physically disconnect the fuel cartridge from system if there is system overheating such as this. 3. Microcontroller failure automatically causes the fuel to shutoff.
6. How is the entire system constructed to prevent unsafe hydrogen emissions?	1. The catalytic heater eliminates hydrogen before the product stream exits the system. 2. The total amount of hydrogen in the system at any one time contains very low energy content (equivalent to less than 1/10 of one drop of methanol, assuming a drop weighs 0.025 g). 3. Systems are designed and tested to emit hydrogen at safe levels. These limits for these emissions are: - Hydrogen emissions are less than 3 cc/min from a point source. At this level, it is impossible to support a flame. - Hydrogen concentration in a 1 m^3 chamber at 10 air changes per hour (ACH) is less than 25% LFL (1% hydrogen). (Source: IEC 62282-6-1) 4. The system is designed to detect hydrogen leaks (through temperature and voltage sensors as outlined in Items 3-5) and automatically shuts down when a leak occurs. The system's microcontroller controls the system functions and will shutoff fuel and air delivery when unacceptable readings are detected. 5. The microcontroller will also physically disconnect the fuel cartridge from system if there is system cooling from a leak failure. 6. Microcontroller failure automatically causes the fuel to shutoff.

7. How are risks of other potentially harmful emissions mitigated? (e.g., methanol, carbon monoxide, hydrogen, formaldehyde, formic acid).	1. Catalytic heater(s) eliminates harmful gases before exiting the system through oxidation of these gases to carbon dioxide and water vapor. 2. The fuel cell stack also helps to eliminate harmful gases before exiting the system through oxidation of these gases to carbon dioxide and water vapor. 3. The system designed and tested to have safe emissions. The limits for potential emissions are: Water — No limit Methanol — 2600 mg/hr Formaldehyde — 0.6 mg/hr Carbon monoxide — 290 mg/hr Carbon dioxide — 60,000 mg/hr Formic acid — 90 mg/hr Methyl formate — 2450 mg/hr The emission rates are based on maintaining safe concentrations in a 1 m^3 chamber with 10 air changes per hour (ACH). This gives a product of 10 ACH • m^3. This product was selected because it covers the reasonably foreseeable environments where micro fuel cell systems will be used. The interior space in a small car and the minimum volume per person on commercial aircraft is at 1 m^3. The minimum ACH used on passenger aircraft is 10 ACH, and the lowest ventilation setting in cars is 10 ACH. Homes and offices may have ACH levels as low as 0.5, but the per person volume is over 20 m^3, so a product of 10 ACH• m^3 is conservative. Note that a seated adult has a carbon dioxide emission rate of 30,000 mg/hr. The fuel cell plus human emission rates are limited to the 9 g/m^3, so the fuel cell emission rate is limited to 60,000 mg/hr. (Source: IEC 62282-6-1)
8. How are risks of buildup in the product enclosure of hydrogen and other flammable gases mitigated?	1. The product enclosure will have multiple vents throughout the product surface. Therefore, buildup of flammable gases will be very unlikely. 2. If flammable gas buildup were to occur from blocking of vents, the system will immediately shutdown from oxygen starvation. 3. Any flammable gas will be diluted by the presence of large amounts of cooling air and nonflammable exhaust gases (e.g., water, carbon dioxide, nitrogen from air). 4. The volume available for gas buildup is limited, since the enclosure will be fully occupied by product components. 5. The system is designed and tested to prevent flammable gas emission, including the maintenance of hydrogen emissions below 25% of the LFL. 6. The leakage of flammable gases, including hydrogen, would cause system cooling, as described in Items 3 and 4. Temperature is continuously monitored through redundant temperature sensors and shuts down under these cooling conditions. The system's microcontroller controls the system functions and will shutoff fuel and air delivery.

	7. The microcontroller will also physically disconnect the fuel cartridge from system if there is this type of cooling. 8. Microcontroller failure automatically causes the fuel to shutoff.
9. What is done to mitigate the risk of a potential worst case scenario of hydrogen buildup, such as hydrogen emissions in a closed suitcase?	1. The catalytic heater will consume oxygen and cause system shutdown well before approaching a flammable mixture. 2. If the catalytic heater is not running, the system will immediate cool and shutdown. 3. The system is designed and tested so that the hydrogen content of exhaust gases never exceed 25% of the LFL. 4. Hydrogen, because of its small molecular size, is difficult to retain.
10. Do the reformer, fuel cell or catalytic heater catalysts present a risk?	1. RMFC catalysts do not present a danger. They are not UN Division 4.2 self heating or pyrophoric substances, nor are they UN Division 4.3 water reactive materials. They do not meet any of the criteria for hazardous materials.
11. How are flammability risks of the fuel cartridge mitigated?	1. The fuel cartridge is physically separated from the reaction point and all high temperatures. This is a significant safety advantage of micro fuel cells. Several layers physically separate the cartridge from the high temperature inside the reformer: the reformer housing, the reformer insulation, internal system components, internal system cooling air, product enclosure, and cartridge housing. 2. The cartridge is maintained at ambient temperatures, and the fuel is in a liquid form. 3. The methanol fuel in the cartridge is far from the flammability and explosive range. The upper explosive limit of methanol is 36%, whereas the cartridge is well above 99% methanol-water fuel. The use of a fuel bladder combined with system design precludes air from mixing with methanol in the cartridge. 4. The cartridge does not contain ignition sources 5. The cartridge body, valve, and connect/ disconnect mechanism are designed and tested to prevent methanol release, as outlined below in Item 12.
12. How is methanol leakage from the fuel cartridge?	1. The fuel cartridge will be designed and tested to demonstrate its ability to maintain integrity with high internal pressures and loss in ambient pressure from high altitudes (>95kPa). 2. The fuel cartridge will be designed and tested to withstand extreme temperatures (-40^{o}C - 85^{o}C). 3. The fuel cartridge will be designed and tested to tolerate drop heights of 1.8 m, vibration (7 Hz - 200 Hz, 1 gn - 8 gn), crushing force of 100 kg. 4. The fuel cartridge components that are in contact with the methanol fuel will be designed and tested to tolerate exposure over product life and throughout product environment (temperature of -40^{o}C - 85^{o}C, pressure differentials of at least 95 kPa, humidity 0-100%).

	5. The fuel cartridge will be 3rd party certified (e.g., a UL product test lab) in accordance with IEC 62282-6-1.
13. Is pressure buildup a risk in the unit?	1. RMFCs are “open” systems. This means that the system is open to ambient pressure. This prevents flow channels from building up in pressure, regardless of the temperature.

Section 5. The IEC safety standard for micro fuel cells

This section provides an overview of the international product safety standard for micro fuel cells being prepared through the International Electrotechnical Commission (IEC).

What is the IEC safety standard for micro fuel cells, and what is its scope?

The International Electrotechnical Commission (IEC) is the electrical counterpart to International Standards Organization (ISO), and the standard (IEC 62282-6-1) is being finalized to ensure safe operation of micro fuel cells in all reasonable uses, including onboard commercial aircraft. The standard addresses RMFCs, among other micro fuel cell technologies and is currently being finalized for international review and comment. Final publication of the standard is expected by the end of 2006.

As outlined in the draft of the standard, its scope is:

> "This consumer safety standard covers fuel cell power systems and fuel cartridges that are wearable or easily carried by hand, providing DC outputs that do not exceed 60 V DC. SELV limits and power outputs that are ≤ 240 VA. As such, the external circuitry are considered circuits that are "SELV" as defined in IEC 60950-1, and are considered to be limited power circuits if further compliance with IEC 60950-1, Section 2.5 is demonstrated. Systems that have internal systems exceeding 60 V DC or 240 VA must be appropriately evaluated in accordance with separate criteria of IEC 60950-1."

What test requirements are covered by this safety standard?

IEC 62282-6-1 contains an extensive range of product safety tests, including: temperature cycling, altitude simulation, vibration, drop, compressive loading, short circuiting, surface temperature, exhaust temperature, long-term storage, internal pressure, and emission tests. Since RMFCs are methanol fuel cells, they will have very similar tests and criteria to DMFCs. In addition, RMFCs have tests requiring auto shutdown with abnormally high temperatures, safe operation under high temperatures, and hydrogen emissions tests (Annex C). The set of tests is designed to conform to all international requirements for commercial aircraft.

What is the process by which a micro fuel cell becomes IEC-certified?

The micro fuel cell manufacturer seeking recognition by the international transportation regulators would be required to sample systems and cartridges to a recognized 3rd party test lab (such as UL) for compliance testing and certification. The test lab would conduct all tests as specified in IEC 62282-6-1 and provide a test report. If the product complies, the certified product would carry a certification mark and other marking indicating compliance with IEC 62282-6-1.

Conclusion

RMFCs offer high levels of portable power safety. The user experiences low surface and exhaust temperatures, and the small amount of hydrogen within the system is only a process intermediate that is not dangerous to the user. The catalytic heater, furthermore, provides a robust means of ensuring conversion of all streams to a safe exhaust of carbon dioxide and water. The high temperature (280^oC) reformer is easily isolated with well known insulators, much like a microprocessor's temperature is isolated from the laptop user. RMFC catalysts are not hazardous materials. The system is open to ambient pressures and therefore does not have pressure buildup from high temperatures. RMFC fuel cartridges are designed to safely withstand all foreseeable stresses in transportation, and the cartridge is well isolated from the reaction point in the RMFC. Finally, the IEC Working Group 8 safety standard (IEC 62282-6-1) provides a rigorous testing for RMFCs, ensuring safe operation.

It is the proposal of the RMFC IEC Safety Task Group that RMFCs are considered along with DMFCs in the class of Methanol Fuel Cells and are approved for onboard usage by passengers on commercial aircraft. This approval will be a key step forward in the coming widespread commercialization of RMFCs as a safe and advanced form of portable power.

Appendix A: Examples of RMFC products

Figure 7. An UltraCell RMFC system for laptop computers

Figure 8. An UltraCell RMFC system for laptop computers

Figure 9. Image model of a Casio RMFC system for laptop computers

Appendix B: RMFC product safety working group contacts

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References

1. Incropera, Frank P., and Dewitt, David P. *Fundamentals of Heat and Mass Transfer*. 5th edition, p. 912. Wiley, 2001.
2. Motorola, Casio, and UltraCell test data.

ICAO Member Briefing

Passenger and Crew Exception for Butane Powered Micro Fuel Cells

June 29, 2005

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Background

As portable electronic devices continue to evolve, current battery technology is not keeping pace. Consumer electric manufacturers are developing micro fuel cell technologies to power the next generation of modern devices. Micro fuel cells represent a completely new technology, utilizing fuels such as butane to generate electrical power, rather than the lithium chemistry found in most rechargeable batteries today.

A comprehensive safety standard (IEC-62282-6-1) has been developed to ensure that this technology is safe in the consumer's hands. This standard compliments the existing standards and regulatory requirements for consumer electronics products. Fuel cell equipment will meet these existing standards for electronic products as well as the new requirements specific to fuel cell equipment.

Based upon rigorous compliance testing, intrinsically safe fuel cell architectures, and the excellent safety record of butane consumer products, we propose a passenger and crew exception for transport and use of butane powered micro fuel cells as carry on items aboard passenger-carrying aircraft.

Butane Fuel Cells

Butane micro fuel cells generate electric power through a chemical reaction between the fuel and the oxygen in air. This reaction coverts the carbon and hydrogen components in butane into carbon dioxide, water and electricity.

Fuel cells are an extremely clean source of power, without the dangerous emissions associated with a combustion process. These devices present an attractive alternative to the ever-increasing volume of Lithium Ion batteries now being brought aboard passenger aircraft.

Butane as a Fuel

The fuel used in butane-powered fuel cells is butane or a butane/propane mix. This is the same material used in disposable lighters, as a propellant in aerosols such as deodorant or hairspray, and as fuel for cordless hair curling irons. Butane has an excellent safety record both as a general consumer item and as a component of many products currently allowed in carry-on baggage.

Under a slight pressure (~250kPa) butane forms a liquid, allowing for convenient, safe storage. Industry has decades of experience producing consumer packaging for butane, and in the exceedingly rare circumstances that a package might be damaged to the extent of generating a leak, the gas quickly dissipates into the air. Only if a leak is coincident with an ignition source does a fire hazard exist. Butane is a completely non-toxic material that presents no health hazard to humans unless in such large quantities that it physically displaces the air we need to breath.

Butane is currently allowed on passenger aircraft in a variety of packages. When shipped as cargo under UN2037, up to 1kg is allowed per outer container and 1 liter per inner receptacle. It is allowed in the cabin as a propellant in aerosol cans, as a fuel in portable curling irons, and in all countries except the US in disposable lighters.

The Table 1 shows a comparison between the proposed butane powered fuel cell cartridges and other materials currently allowed in the cabin of passenger aircraft.

Safety Assurance

The architecture of the butane fuel cell system provides fail-safe features beyond those found in most other types of fuel cells. The system only operates when a balance is maintained between the fuel power being provided, the temperature of the fuel cell, and the amount of electrical energy being provided to the load. Any significant change to this balance stops all reactions and the system shuts down. Heat loss during the reaction is minimized though use of a vacuum package, similar to a light bulb or a thermos bottle. If the seal to the fuel cell reactor package is damaged, even slightly, the vacuum would be lost and the device temperature would drop dramatically (to ~70°C), stopping all reactions.

Table 1: Comparison of Butane Fuel Cell Cartridge to Consumer Products Currently Included in a Carry-On Exception

Product	Volume	Notes
Fuel Cell Cartridge	25 to 200 ml butane	No release mechanism or ignition source. Included safety interlock to prevent valve from opening unless properly mated to fuel cell system. Certified to IEC safety standard.
Aerosol Hairspray	260 ml butane 200 ml ethanol	Contains both a flammable gas propellant and a flammable liquid product. Includes a release mechanism.
Cigarette Lighter	15 ml butane	Includes release mechanism and ignition source
Portable Curling Iron	25 ml butane	Includes release mechanism and ignition source
Perfume	100 ml	Flammable liquid. Up to 90% alcohol by weight.
Alcohol	5 liter	Flammable liquid in a glass container, up to 70% alcohol by weight.

No ignition source exists in the butane fuel cell system, preventing fire even in the unlikely event of a fuel leak. In addition, the entrance and exhaust ports of the fuel cell microstack's vacuum package are sized below the Maximum Experimental Safe Gap (MESG), the minimum size required for a flame to propagate. This prevents any possibility of the fuel cell reaction providing an ignition source external to its vacuum package.

The butane fuel cell system contains control electronics that monitor system parameters, can trigger a system shutdown and cease the flow of fuel in the case of any critical failures, including abnormal temperatures, excessive fuel consumption, excess current draw, unrecoverable voltage drop, or similar events. Through this comprehensive monitoring, the system will also detect an abnormal external condition, such as excessive load or short-circuits, and cease operation. System electronics are designed and tested to necessary levels of electromagnetic compatibility (EMC) to ensure reliable operation of the safety control systems and prevent affect of any other near-by electronic devices.

The butane fuel cell cartridge is limited to 200ml of fuel. The cartridge is designed to extremely stringent specifications for temperature, pressure, vibration, drop, crush, child resistance, tamper resistance, and material compatibility to assure no leakage in both use and mis-use situations. The cartridge and system fuel connectors only allow fuel to flow when sealed to the proper mating connector. Upon disconnection from the fuel cell power unit, the connectors shut and stop fuel flow immediately. The IEC-62282-6-1 safety standard includes strict 'no leakage' criteria for butane cartridges, even during repeated mating and un-mating cycles.

The design of the fuel cell cartridge and system is certified to meet the IEC-62282-6-1 Micro Fuel Cell Safety standard. This standard specifies extensive product requirements and associated type testing, assuring product safety in both normal use and reasonable abuse situations. Specific requires include pressure differential tests (altitude simulation), vibration tests, high temperature exposure and temperature cycling tests, drop tests, compressive loading tests, short circuit, exhaust gas temperature, cartridge connection cycling tests, and emission tests. The safety standard is on schedule for final approval by the IEC before the end of 2006.

Appendix A: Risk Mitigation Analysis

A risk and safety analysis performed on the butane fuel cell system highlights various product design controls and qualification testing activities to prevent safety critical failures and eliminate unacceptable risks. The table below summarizes the potential risks and associated mitigations that can be demonstrated through physical analysis and/or testing to assure safety thought the life of the product.

Note: Bracketed numbers the “Risk Mitigations” column indicate corresponding numbered items in the “Risk Description” column.

#	Risk Description	Risk Mitigations
1	Butane leaks out of cartridge from exposure to environmental or handling stress through: 1. High temperature 2. Temperature cycling 3. Altitude change 4. Vibration 5. Dropping 6. Crushing 7. System or Cartridge component or material degradation leading to: - damage to equipment or personal injury from ignition of flammable gas	(1,2,3,4,5,6,7) The fuel cell system will be designed and tested to assure that there is no available ignition source for leaked fuel. (1,2,3) The fuel cartridge will be designed and tested for excess over pressure withstand capability (caused by high temperatures and altitude change in aircraft). (1,2) The fuel cartridge will be designed to withstand extreme temperatures (70℃) and temperature cycling (55℃ to -40℃) without leaking fuel. (4,5,6) The fuel cell cartridge will be designed to meet normal use and reasonable abuse vibration, drop and crush test specifications. (7) Fuel cartridge components/materials which are in direct contact with butane will be checked and tested for suitability for use with butane over the life of the product. (1,2,3,4,5,6,7) The butane fuel cell system will be safety certified to the IEC-62282-6-1 Micro Fuel Cell Safety standard which explicitly calls for extreme temperature, temperature cycling, altitude change, vibration, drop, crush and critical components material qualification and compatibility with fuel tests. (1,2,3,4,5,6,7) Fuel cartridge and fuel cell system will be tested by an independent laboratory as part of the IEC-62282-6-1 certification process. In the unlikely event that, despite all safeguards, butane fuel was to leak from the system, it would readily disperse into the air to a concentration less than the lower flammability limit.
2	1. Child gains access to the butane fuel inside the cartridge or the fuel cell system Or	(1) Cartridge and fuel cell system components will be designed and tested to meet child resistant criteria. (1,2) The butane fuel presents no toxicity hazard and no asphyxiation hazard in the quantities

	2. Butane fuel cell system or cartridge) can sustain damage under reasonable consumer use and abuse situations such that the fuel can leak or be accessed leading to: - fire or personal injury	reasonable for use with micro fuel cells, even when multiple spare cartridges are considered. (1,2) Product will be safety certified to the IEC Micro Fuel Cell standard which is a consumer based safety standard. The committee developing the standard has made all efforts to ensure all anticipated use and reasonable abuse conditions are mentioned in the standard. The standard references other consumer product safety standards, such as safety standards for consumer information technology products. (1,2) Cartridge and fuel cell system will be designed to ensure no leak occurs as per the risk mitigations mentioned in 1. above. In addition, no ignition source exists in either the fuel cell cartridge or the fuel cell system. (1,2) The butane micro fuel cell system will be designed as tamper resistant, such that without special tools (e.g., screw driver, metal knife, hammer) the system cannot be taken apart and the fuel accessed.
3	Dangerous emissions during operation of the butane powered fuel cell. leading to: - personal injury	Butane fuel cells function by chemically converting butane and air into water and carbon dioxide. CO2 and all other potentially harmful emissions will be evaluated as per the emissions testing requirements of IEC-62282-6-1 standard to assure emission are below the World Health Organization limits for occupational exposure. Labels will be placed on the product and wording included in accompanying literature, instructing the user of the CO2 emissions and recommending use in well ventilated areas or CO2 monitored and controlled areas. Note: A 25 Watt butane fuel cell system's CO2 emissions is equivalent to an average human adult's (70 kg, sitting at rest) CO2 respiration rate. This is also equivalent to one-tenth of the CO2 released by a 2 kg block of dry ice, as currently allowed as a carry-on item.
4	Operation of the butane fuel cell system may cause oxygen depletion to below an acceptable level for comfort levels in passenger cabins in aircraft. (19.5% minimum OSHA occupational level, 18% level is considered unsafe threshold for humans). leading to: - personal injury due to oxygen	A 25 W butane fuel cell operated in a 1 cubic meter volume with 10 air changes per hour (representative of minimum cabin volume per passenger and minimum air change rate) would decrease air oxygen content from 20.90% to 20.72%. Each passenger in a full aircraft could operate five 25 W fuel cells without reaching the OSHA guideline limit. Note: A 25 Watt butane fuel cell system's O2 consumption is equivalent to an adult's (70 kg,

	depletion.	sitting at rest) O2 consumption rate. A 5 W fuel cell would consume 1/5th of an adult's O2 consumption rate.
5	The product may present a flammability hazard as materials coupled with fuel vapor production, ignition sources, and electrical heat may cause fires. leading to: - damage to equipment or personal injury	Materials of components which are in direct contact with fuel will not support a flame. Auto ignition temperature of butane is 365℃, well above the allowable temperature rise of system components per the IEC-60950 electronics standard. All electronics in the fuel cell system will be non- arcing and non-sparking. IEC-62282-6-1 standard calls for short circuit testing and checks for flammability rating of materials. The fuel cell control system monitors current draw and will trigger system shut down on an over-current, short circuit, or similar fault situation. Response of system to short circuit testing will be verified as part of the IEC-62282-6-1 certification process. Labels will be placed on the product or included with accompanying literature, warning against exposing system to open fire.

Appendix B: IEC 62282-6-1 Test Criteria

Following is an abridged list of tests associated with certification to the IEC-62282-6-1 Micro Fuel Cell Safety Standard.

Pressure differential tests (altitude simulation)	The greater of 95kPa or Two times the fuel vapor pressure at 55°C
Vibration tests	17 to 200 Hz for 3 hours total with accelerations up to 8 g's
High temperature exposure tests	Four hours at 70ºC
Temperature cycling tests	Two cycles of -45ºC to 55 ºC with four hour soaks at temperatures
Drop tests	System: 1.2 m; Cartridge: 1.8 m
Compressive loading tests	System: 25 kg; Cartridge: 100 kg
Short circuit	0.1 ohms for 5 minutes
Exhaust gas temperature tests	Less than 70 ºC
Long-term storage	28 days
Cartridge connection cycling tests	System: 1000 cycles; Cartridge: 10 cycles
Emission tests	All emission must be below limits recommended by the WHO/ILO for occupational safety.

Certification criteria includes a stringent "no leakage" requirement which is below the minimum mass loss rate capable of:

1. sustaining a flame
2. producing the Lower Flammability Limit in a 1 cubic meter volume with one air change per hour